
# SLURM Resource and Job Management in HPC

Users and Administrators Tutorial

- **Part 1: Basics**
  - **Overview, Architecture, Configuration files, Partitions, Plugins, Reservations**
- **Part 2: Advanced Configuration**
  - **Accounting, Scheduling, Allocation, Network Topology Placement, Generic Resources Management, Energy Reduction Techniques**
- **Part 3: Experts Configuration**
  - **Isolation with cgroups, Power Management, Simulation and evaluation**

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# SLURM sources and Documentation

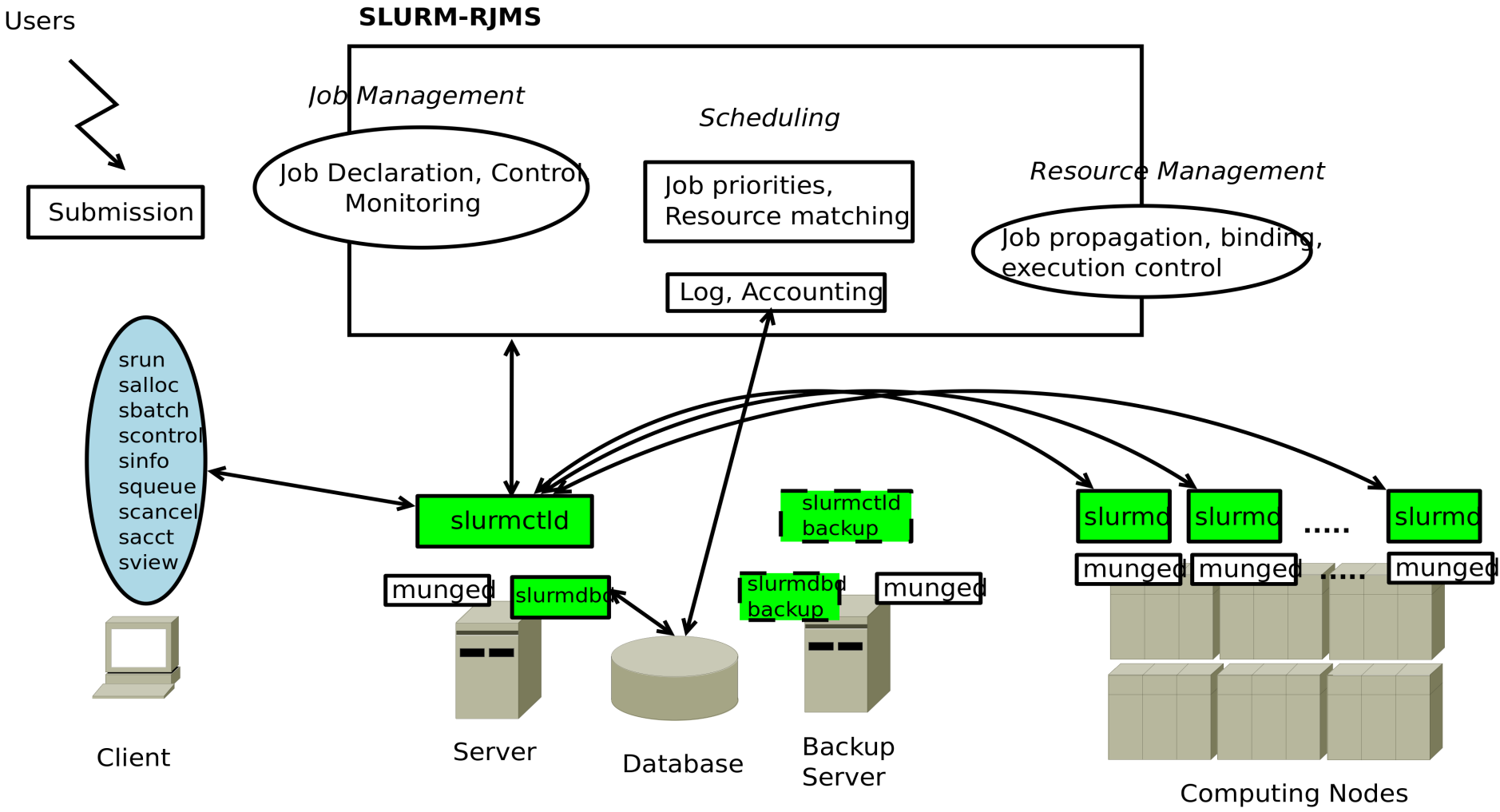
**Slurm sources :**
**-** Download a repo (stable or development) from: http://www.schedmd.com/#repos
- Or the latest code from: *git clone git://github.com/SchedMD/slurm.git*

-For User and Admins latest **documentation**:
http://slurm.schedmd.com/documentation.html

-Detailed **man pages** for commands and configuration files
http://slurm.schedmd.com/man_index.html

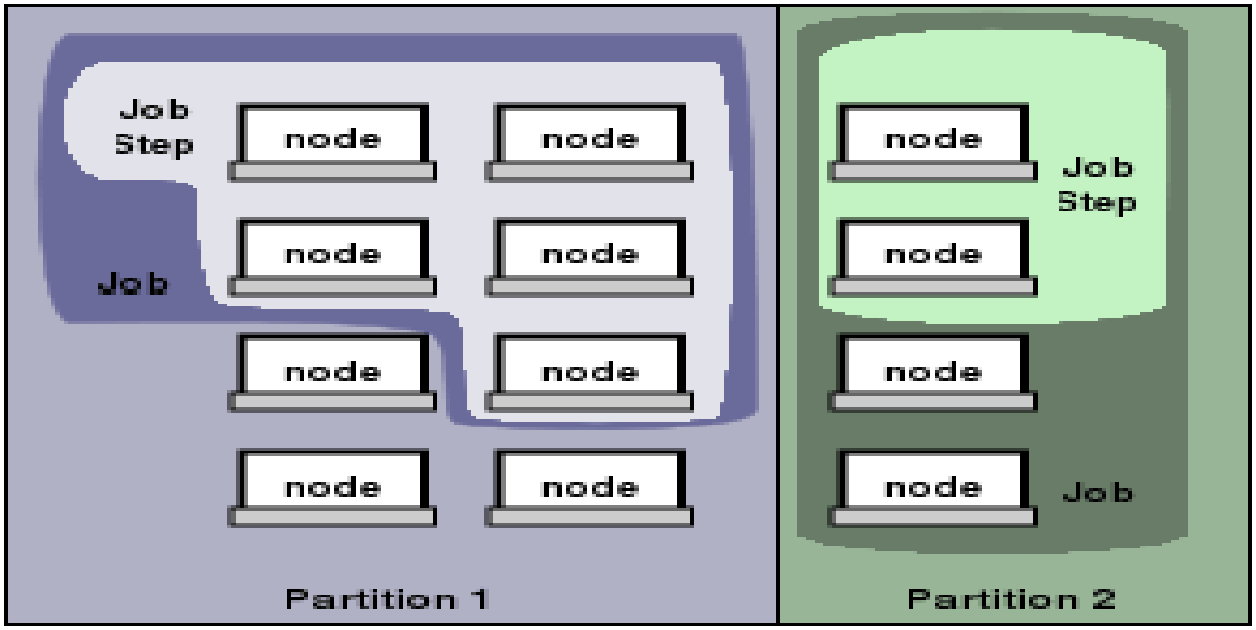
-All SLURM related **publications and presentations:**
http://slurm.schedmd.com/publications.html

# SLURM Architecture



# SLURM Terms

- **Computing node** Computer used for the execution of programs
- **Partition** Group of nodes into logical sets
- **Job** allocation of resources assigned to a user for some time
- **Step** sets of (possible parallel) tasks with a job



# SLURM Principles

- Architecture Design:
  - one central controller daemon **slurmctld**
  - A daemon upon each computing node **slurmd**
  - One central daemon for the database controls slurmdbd
- Principal Concepts:
  - a general purpose **plugin mechanism** (for features such as scheduling policies, process tracking, etc)
  - the **partitions** which represent group of nodes with specific characteristics (job limits, access controls, etc)
  - one **queue** of pending work
  - The **job steps** which are sets of (possibly parallel) tasks within a job

# User Commands

**srun** allocate resources ( number of nodes, tasks, partition, constraints, etc.) launch a job that will execute on each allocated cpu.

**salloc** allocate resources (nodes, tasks, partition, etc.), either run a command or start a shell. Request launch srun from shell. (interactive commands within one allocation)

**sbatch** allocate resources (nodes, tasks, partition, etc.) Launch a script containing sruns for series of steps.

**sbcast** transmit file to all nodes of a running job. Used in sbatch or salloc.

**sattach** attach to running job for debuggers.

# User & Admin Commands

**sinfo** display characteristics of partitions
**squeue** display jobs and their state
**scancel** cancel a job or set of jobs.
**scontrol** display and changes characteristics of jobs, nodes, partitions.
**sstat** show status of running jobs.
**sacct** display accounting information on jobs.
**sprio** show factors that comprise a jobs scheduling priority
**smap** graphically show information on jobs, nodes, partitions

# Admin Commands

**sacctmgr** setup accounts, specify limitations on users and groups.

**sreport** display information from accounting database on jobs, users, clusters.

**sview** graphical view of cluster. Display and change characteristics of jobs, nodes, partitions.

**strigger** show, set, clear event triggers. Events are usually system events such as an equipement failure.

**sshare** view sharing information from multifactor plugin.

# Simple Example of usage

```
>srun -p P2 -N2 -n4 sleep 120 &
>srun -p P3 sleep 120 &
>srun -w trek0 sleep 120 &
>sleep 1
srun: job 108 queued and waiting for resources

>sinfo
PARTITION AVAIL  TIMELIMIT  NODES  STATE NODELIST
all*         up   infinite      3  alloc trek[0-2]
all*         up   infinite      1   idle trek3
P2           up   infinite      3  alloc trek[0-2]
P2           up   infinite      1   idle trek3
P3           up   infinite      3  alloc trek[0-2]
P3           up   infinite      1   idle trek3

>squeue
JOBID PARTITION     NAME     USER  ST       TIME  NODES NODELIST(REASON)
    106        P2    sleep    slurm   R       0:01      2 trek[1-2]
    107        P3    sleep    slurm   R       0:01      1 trek1
    108       all    sleep    slurm  PD       0:00      1 (Resources)
    105       all    sleep    slurm   R       0:02      1 trek0
```

# Simple Example of usage

```
> scontrol show job 108

JobId=108 Name=sleep
   UserId=slurm(200) GroupId=slurm(200)
   Priority=4294901733 Account=slurm QOS=normal
   JobState=PENDING Reason=Resources Dependency=(null)
   Requeue=1 Restarts=0 BatchFlag=0 ExitCode=0:0
   RunTime=00:00:00 TimeLimit=UNLIMITED TimeMin=N/A
   SubmitTime=2011-07-12T09:15:39 EligibleTime=2011-07-12T09:15:39
   StartTime=2012-07-11T09:15:38 EndTime=Unknown
   PreemptTime=NO_VAL SuspendTime=None SecsPreSuspend=0
   Partition=all AllocNode:Sid=sulu:8023
   ReqNodeList=trek0 ExcNodeList=(null)
   NodeList=(null)
   NumNodes=1 NumCPUs=1 CPUs/Task=1 ReqS:C:T=*:*:*
   MinCPUsNode=1 MinMemoryNode=0 MinTmpDiskNode=0
   Features=(null) Gres=(null) Reservation=(null)
   Shared=OK Contiguous=0 Licenses=(null) Network=(null)
   Command=/bin/sleep
   WorkDir=/app/slurm/rbs/_Scripts
   Switches=0 Wait-for-Switch=0 (seconds)
```

# Configuration

**Slurm configuration:** Through configuration **files** responsible, for the function of different **daemons** present on the management and the computing nodes

**slurm.conf**
- Indispensable on all nodes (management-compute)

**slurmdbd.conf**
- Used if slurmdbd accounting
- Only on management node

**topology.conf**
- Used if topology plugin activated
- Indispensable on all nodes (management-compute)

**gres.conf**
- Used if gres plugin activated
- Only on computing nodes

**cgroup.conf**
- Used if cgroup plugin activated
- Only on computing nodes

# Configuration files

**slurm.conf**
- Low level configuration
- Management policies
- Scheduling policies
- Allocation policies
- Node definition
- Partition definition

**slurmdbd.conf**
- Type of persistent storage (DB)
- Location of storage

**topology.conf**
- Switch hierarchy

**gres.conf**
- Generic resources details
- Device files

**cgroup.conf**
- Mount point
- Release agent path
- Cgroup subsystems parameters

| | Controller | Compute node |
|---|---|---|
| Mandatory | slurm.conf<br>slurmdbd.conf | slurm.conf |
| Optional | prologs<br>epilogs<br>topology.conf | gres.conf<br>cgroup.conf<br>topology.conf |

# Configuration (slurm.conf) – Part 1

## Node definition

- Characteristics (sockets, cores, threads, memory, features)
- Network addresses

## Partition definition

- Set of nodes
- Sharing
- Priority/preemption

```
 # Compute Nodes
NodeName=cuzco[1-10] Procs=16 Sockets=2 CoresPerSocket=8 ThreadsPerCore=1 State=UNKNOWN RealMemory=38000
NodeName=cuzco[10-20] Procs=32 Sockets=2 CoresPerSocket=8 ThreadsPerCore=2 State=UNKNOWN RealMemory=46000

 # Partitioning
PartitionName=exclusive Nodes=cuzco[1-20] MaxTime=INFINITE State=UP Priority=10 Shared=Exclusive
PartitionName=shared Nodes=berlin[1-20] Default=YES MaxTime=INFINITE State=UP Priority=30
PartitionName=procs16 Nodes=berlin[1-10] MaxTime=INFINITE State=UP Priority=30
PartitionName=procs32 Nodes=berlin[10-20] MaxTime=INFINITE State=UP Priority=30
```

# Partitions

- Partitions are used in SLURM to group nodes/resources characteristics

**Partition 1:** 32 cores and high_memory

**Partition 2:** 32 cores and low_memory

**Partition 3:** 64 cores

# More on Partitions

**Shared Option**
Controls the ability of the partition to execute more than one job on a resource (node, socket, core)

**EXCLUSIVE** allocates entire node (overrides cons_res ability to allocate cores and sockets to multiple jobs)
**NO** sharing of any resource.
**YES** all resources can be shared, unless user specifies –exclusive on srun | salloc | sbatch

**Important Note:** To view the particular parameters of partitions users can use the “scontrol show partitions” command

# Configuration (slurm.conf) – Part 2

```
#slurm.conf

# Basic parameters
ClusterName=cuzco
ControlMachine=cuzco0
#ControlAddr=127.0.0.1
SlurmUser=slurm
SlurmctldPort=6817
SlurmdPort=6818
AuthType=auth/munge

# States saving
StateSaveLocation=/var/spool/slurm
SlurmdSpoolDir=/var/spool/slurmd.%n
SlurmctldPidFile=/var/run/slurmctld.pid
SlurmdPidFile=/var/run/slurmd.%n.pid

# Logging
SlurmctldDebug=5
SlurmctldLogFile=/var/log/slurmctld.log
SlurmdDebug=5
SlurmdLogFile=/var/log/slurmd.%n.log

# Timers
SlurmctldTimeout=300
SlurmdTimeout=300
```

**Management Policies**

- Location of controllers, spool, state info
- Authentication
- Logging
- Prolog / epilog scripts

# Configuration (slurm.conf) – Part 3

```
# Process-Task tracking
ProctrackType=proctrack/linuxproc
TaskPlugin=task/affinity
TaskPluginParam=Cpusets

# Selection of Resources
SelectType=select/cons_res
SelectTypeParameters= CR_Core_Memory

# Scheduling
SchedulerType=sched/backfill
FastSchedule=1
PreemptMode=REQUEUE
PreemptType=preempt/qos
FastSchedule=1
```

## Scheduling policies

- Priority
- Preemption
- Backfill

## Allocation policies

- Entire nodes or 'consumable resources'
- Task Affinity (lock task on CPU)
- Topology (minimum number of switches)

# Plugins in SLURM

- **Authentication** (i.e. munge,)
- **Job Accounting Gather** (i.e. linux, cgroups)
- **Accounting Storage** (i.e. mysql, postgres)
- **Generic Resources (GRES)** (i.e. gpu, nic)
- **Job Submission** (i.e. partitions, lua)
- **MPI** (i.e. openmpi, pmi2)
- **Energy Accounting** (i.e. rapl,ipmi)
- **Preemption** (i.e. partitions,qos)
- **Priority** (i.e. basic,multifactor)
- **Process Tracking** (i.e. linux,cgroup)
- **Scheduler** (i.e. builtin,backfill)
- **Resource Selection** (i.e. linear,cons_res)
- **Task** (i.e. affinity,cgroups)
- **Topology** (i.e. tree,3d_torus)

# Starting SLURM

- Once the principal configuration parameters are correctly set the services can be started on management and computing nodes by **launching the particular scripts** on all nodes:
  /etc/init.d/slurm {start, stop, restart, …}

- Alternatively the services can be started by **executing the commands** slurmctld on the controller and slurmd on the computing nodes

- The services are normally launched in the background with logging in the particular files set in the slurm.conf. However it is possible to **start the deamons in the foreground** with -D followed by v for different verbosity levels. This is useful for testing.
  slurmctld -Dvvvvvv
  slurmd -Dvvvvvv

# Job Submission

**srun** launches a job that allocates resources (number of nodes, tasks, etc.) and is executed on each allocated cpu.

Some basic parameters for **srun** command:

**-N** number of nodes

**-n** number of tasks

**--exclusive** for exclusive acces of nodes

Example: *srun -N2 -n1 –exclusive hostname*

**sbatch** launches a script that allocates resources and may contain multiple sruns for series of steps

Basic parameters similar with srun

Execution script may contain #SBATCH options to declare the parameters:

Example sbatch script:

```
>cat job.sh
 #!/bin/sh
 #SBATCH -N2
 #SBATCH -n2
 #SBATCH –exlusive
 srun hostname
```

Example launching sbatch script:

```
>sbatch ./job.sh
Submitted batch job 18
>cat slurm-18.out
cuzco29
cuzco30
```

# Job Submission

**salloc** is used to allocate resources for a job interactively. Typically this is used to allocate resources and spawn a **shell**. The shell be used to execute srun commands

Basic parameters similar with srun and sbatch
It will also set environmental variables such as:
SLURM_JOB_ID
SLURM_TASKS_PER_NODE
SLURM_JOB_NODELIST

```
Example launching salloc:
>salloc -N2
Salloc Granted job allocation 145
>srun -N2
 cuzco29
 cuzco30
>echo $SLURM_JOB_ID
145
```

# Job and node monitoring

**squeue** display jobs and their state

Basic parameters for **squeue** command:
**-a** Display info about all jobs and partitions
**-l** Report more info concerning all jobs
**-j <job_list>** Report more info about particular job or jobs
Example: *squeue -l -j 12,13*

**scontrol** can display and change characteristics of jobs, nodes, partitions

Command **scontrol** for detailed info about job or jobs:
Example: *scontrol show job <JobID>*

**sinfo** display node and partition oriented states and characteristics

Command **sinfo** for node oriented information
Example: *sinfo -Nel*

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Example: *sinfo -Nel*

# Job cancelation

**scancel** cancel a pending or running job, set of jobs or send a signal to a job or set of job

Basic parameters for **scancel** command:
**--signal** to send a signal to a job
**Scancel <job-id>** to cancel the job

# Example Exercise

Launch a simple job of 2 tasks upon 2 nodes that sleeps for 60 seconds and monitor its execution and characteristics

```
[georgioy@cuzco27 ~]$ srun -N2 -n2 sleep 60&
[georgioy@cuzco27 ~]$ squeue
  JOBID PARTITION     NAME     USER  ST       TIME  NODES NODELIST(REASON)
      9       all    sleep georgioy   R       0:03      2 cuzco[29-30]
[georgioy@cuzco27 ~]$ scontrol show job 9
JobId=9 Name=sleep
   UserId=georgioy(50071) GroupId=bull(1638)
   Priority=132 Account=students QOS=devel
   JobState=COMPLETED Reason=None Dependency=(null)
   Requeue=1 Restarts=0 BatchFlag=0 ExitCode=0:0
   RunTime=00:01:01 TimeLimit=UNLIMITED TimeMin=N/A
   SubmitTime=2011-09-02T13:58:39 EligibleTime=2011-09-02T13:58:39
   StartTime=2011-09-02T13:58:39 EndTime=2011-09-02T13:59:40
   PreemptTime=None SuspendTime=None SecsPreSuspend=0
   Partition=all AllocNode:Sid=cuzco27:7952
   ReqNodeList=(null) ExcNodeList=(null)
   NodeList=cuzco[29-30]
   BatchHost=cuzco29
   Command=/bin/sleep
   WorkDir=/home_nfs/georgioy
   ...
```

# Hands-ON Exercises

**1)** Configure one new partition with only half of the available nodes and set a time-limit of 2 minutes. Launch a job running a simple 'sleep 300' and observe what happens.

**2)** Set two different partitions that have the same resources but one enables Exclusive allocation and the other allows sharing of nodes. Observe the logging in the particular files.

**3)** Start slurm services in foreground and observe the outputs. Verify that everything Is set correctly and restart in the background

# Hands-ON Exercises

**4)** Create an interactive job that will ask for 3 tasks on 3 nodes and then launch a step that prints the hostname of each node.
Monitor the execution of the job and the state of the nodes.

**5)** Create a job script that asks for 2 tasks on 2 nodes and launches a step that sleeps for 4 minutes.
Monitor the execution of the job and the state of the nodes.
After some time cancel the job and monitor the state of the nodes.

**6)** Create a job script that asks for 6 tasks in total with 2 tasks per node and print the number of the JOB_ID and the number of cpus per node.
Redirect the output on a particular file using the existing parameter.
Execute the script and check out its result upon the created output file.

# Reservations

**scontrol** command can be also used for reservations
It provides the ability to create, update and delete advanced reservations for resources allocations

Basic parameters that need to be used:
Starttime,Duration, User, NodeCnt or NodeList
Once the reservation is made the user can submit a job upon the reserved Resources and this job will start on the starttime.

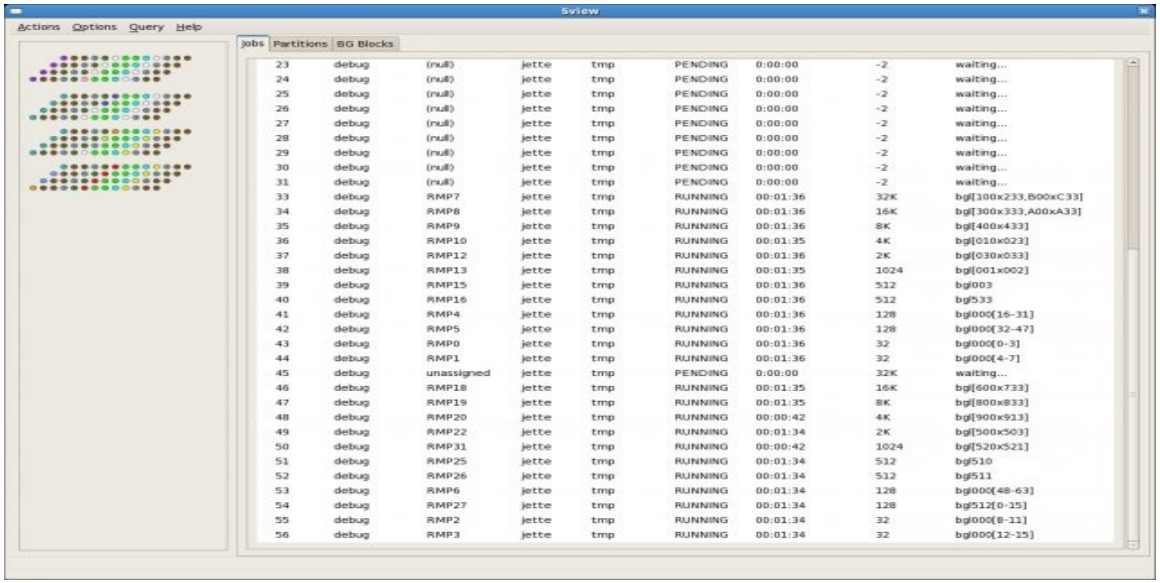
Examples:

```
>scontrol: create res StartTime=2009-04-01T08:00:00 Duration=5:00:00 Users=toto NodeCnt=10
      Reservation created: toto_1
>scontrol: update Reservation=toto_1 Flags=Overlap NodeCnt=20
```

An alternative way to start a job in a particular moment in the future is the –begin-time option of the submission commands

# Visualization Interface

**sview** graphical view of cluster resources, partitions and Jobs. Priviledged users have the ability to change various characteristics of resources, partitions, jobs and to submit sbatch jobs.



# Hands-ON Exercises

**7)** Create a reservation that will ask for 2 CPUs of 2 nodes, that will start after 5 minutes and that will last for 10 minutes. Launch a simple sbatch script to be executed upon this reservation.

**8)** Launch a simple srun job that will start after some minutes and observe its execution with sview

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# SLURM Accounting

- Accounting based upon Mysql database
- Robust and scalable (confirmed upon Tera100 cluster)
- Command for database and accounting configuration: *sacctmgr*
- **Fairsharing and Preemption** scheduling techniques based upon the accounting infrastructure

```
>sacctmgr add cluster snowflake
>sacctmgr add account users Cluster=snowflake Description="none" Organization="none"
>sacctmgr list users
      User    Def Acct     Admin
---------- ---------- ---------
      gohn    students       None
      root        root Administ+
     slurm professors       None
```

# Accounting

## Commands

**Sacct** reports resource usage for running or terminated jobs.
**Sstat** reports on running jobs, including imbalance between tasks.
**Sreport** generates reports based on jobs executed in a time interval.
**Sacctmgr** is used to create account and modify account settings.

## Plugins associated with resource accounting

**AccountingStorageType** controls how information is recorded (MySQLI with SlurmDBD is best)
**JobAccntGatherType** controls the mechanism used to gather data. (OS Dependent)
**JobCompType** controls how job completion information is recorded.

# Accounting (associations)

An Association is a combination of a Cluster, a User, and an Account.

- An accounting database may be used by multiple **Clusters**.
- **Account** is a slurm entity.
- **User** is a Linux user.

Use –account srun option.

With associations, a user may have different privileges on different clusters.

A user may also be able to use different accounts, with different privileges.

Multiple users may launch jobs on a linux account.

# Sacctmgr

**Account Options**
**Clusters** to which the Account has access
**Name**, **Description** and **Organization**.
**Parent** is the name of an account for which this account is a child.

**User Options**
**Account(s)** to which the user belongs.
**AdminLevel** is accounting privileges (for sacctmgr). None, Operator, Admin
**Cluster** limits clusters on which accounts user can be added to.
**DefaultAccount** is the account for the user if an account is not specified on srun
**Partition** is the a partition an association applies to.

# Accounting Limits Enforcement

If a user has a limit set SLURM will read in those, if not we will refer to the account associated with the job. If the account doesn't have the limit set we will refer to the cluster's limits. If the cluster doesn't have the limit set no limit will be enforced.

Some (but not all limits are)

**Fairshare=** Integer value used for determining priority. Essentially this is the amount of claim this association and it's children have to the above system. Can also be the string "parent", this means that the parent association is used for fairshare.

**GrpCPUMins=** A hard limit of cpu minutes to be used by jobs running from this association and its children. If this limit is reached all jobs running in this group will be killed, and no new jobs will be allowed to run. (GrpCPUs, GrpJobs, GrpNodes, GrpSubmitJobs, GrpWall)

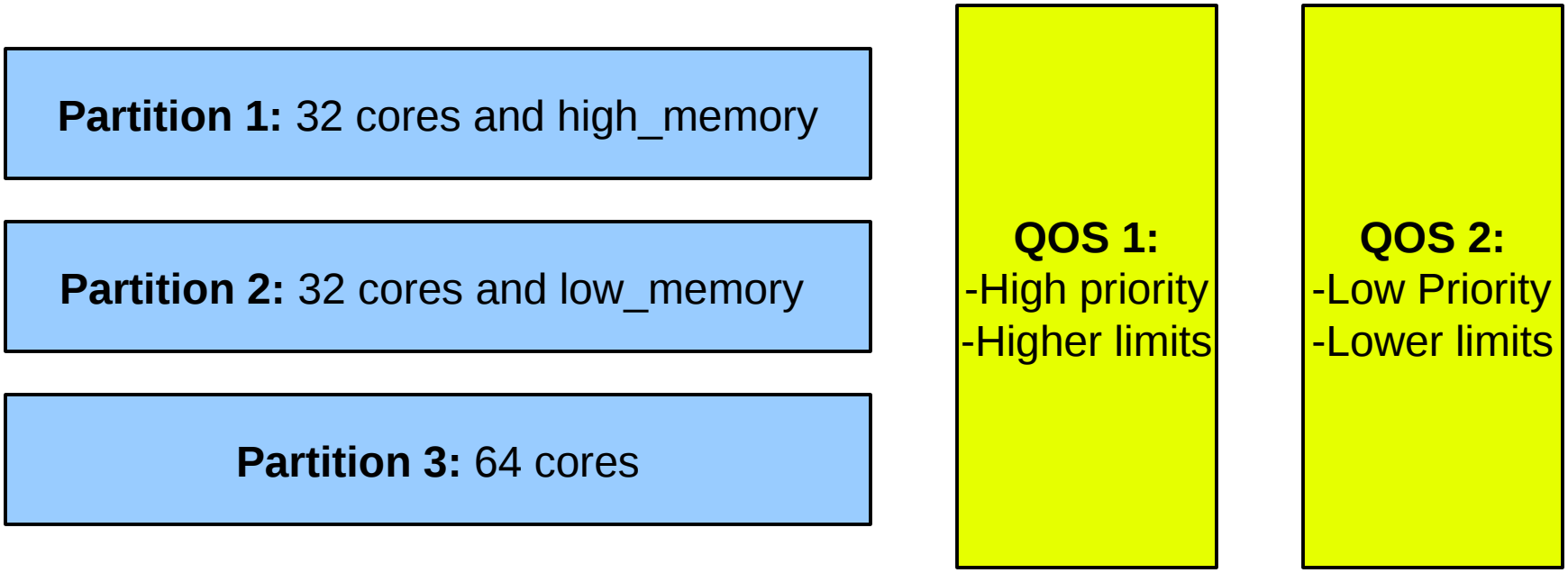
**MaxCPUMinsPerJob=** A limit of cpu minutes to be used by jobs running from this association. If this limit is reached the job will be killed will be allowed to run. (MaxCPUsPerJob, MaxJobs, MaxNodesPerJob, MaxSubmitJobs, MaxWallDurationPerJob)

**QOS** (quality of service) comma separated list of QOS's this association is able to run.

**Important Note:** To activate the accounting limitations and QOSyou need to add the following parameter in slurm.conf, distribute the slurm.conf on all nodes and restart the deamons: AccountingStorageEnforce=limits, qos

# Partitions and QOS

- Partitions and QOS are used in SLURM to group nodes and jobs characteristics
- The use of **Partitions** and **QOS** (Quality of Services) entities in SLURM is orthogonal:
  - Partitions for grouping resources characteristics
  - QOS for grouping limitations and priorities



# Partitions and QOS Configuration

**Partitions Configuration:**
In slurm.conf file

```
# Partition Definitions
PartitionName=all Nodes=trek[0-3] Shared=NO Default=YES
PartitionName=P2 Nodes=trek[0-3] Shared=NO Priority=2 PreemptMode=CANCEL
PartitionName=P3 Nodes=trek[0-3] Shared=Exclusive Priority=3 PreemptMode=REQUEUE
```

**QOS Configuration:**
In Database

```
>sacctmgr add qos name=lowprio priority=10 PreemptMode=Cancel GrpCPUs=10 MaxWall=60 MaxJobs=20
>sacctmgr add qos name=hiprio priority=100 Preempt=lowprio GrpCPUs=40 MaxWall=120 MaxJobs=50
>sacctmgr list qos
      Name   Priority Preempt PreemptMode     GrpCPUs  MaxJobs  MaxWall
---------- ---------- ---------- ---------- ----------- ---------------------------------------- ---------- -------- ----------- -------
   lowprio         10                    cancel            10           20          60
    hiprio        100    lowprio                           40           50         120
```

# More on QOS

**Used to provide detailed limitations and prioritiees on jobs**

**Every user/account will have multiple allowed QOS upon which he may send jobs with the –qos parameter but only one default QOS in case he doesn't precise a –qos parameter in his submission**

**Important Note:** To view the particular parameters of QOS provided by the admins users can use the “sacctmgr show associations” command

# Usage Guide – Accounting

**sacct** displays accounting information for jobs and steps

Some basic parameters for **sacct** command:
**-b** Displays a brief listing (jobid,status,exitcode)
**-l** a long listing of jobs characteristics
**--format <param1,param2,>** to select the actual fields to be shown

Example:

```
>sacct –format=jobid,elapsed,ncpus,ntasks,state
# sacct --format=jobid,elapsed,ncpus,ntasks,state
Jobid    Elapsed      Ncpus   Ntasks     State
---------- ---------- ---------- -------- ----------
3            00:01:30          2        1 COMPLETED
3.0          00:01:30          2        1 COMPLETED
4            00:00:00          2        2 COMPLETED
4.0          00:00:01          2        2 COMPLETED
5            00:01:23          2        1 COMPLETED
5.0          00:01:31          2        1 COMPLETED
```

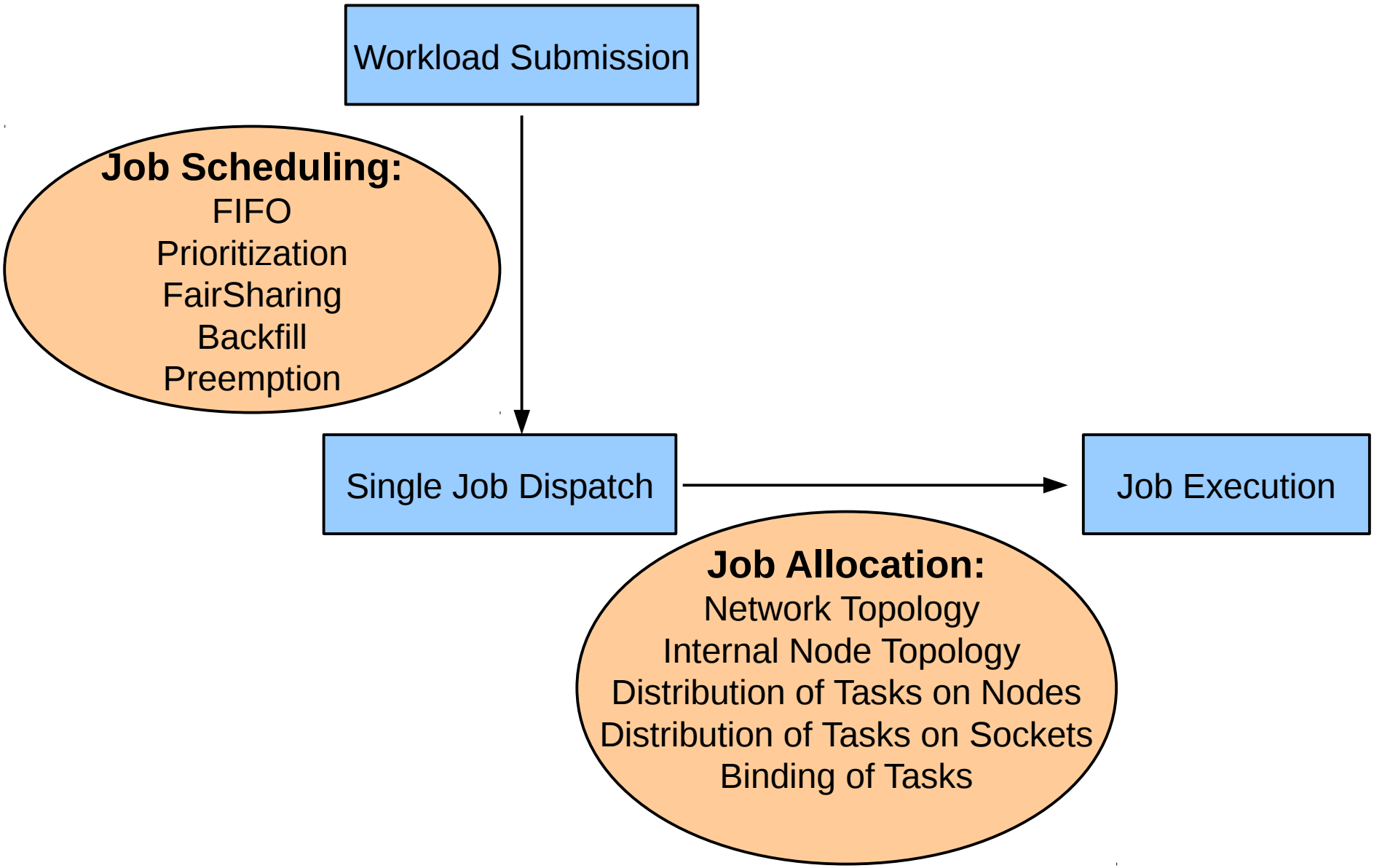
# Usage Guide – Reporting

**sreport** generates reports of job usage and cluster utilization

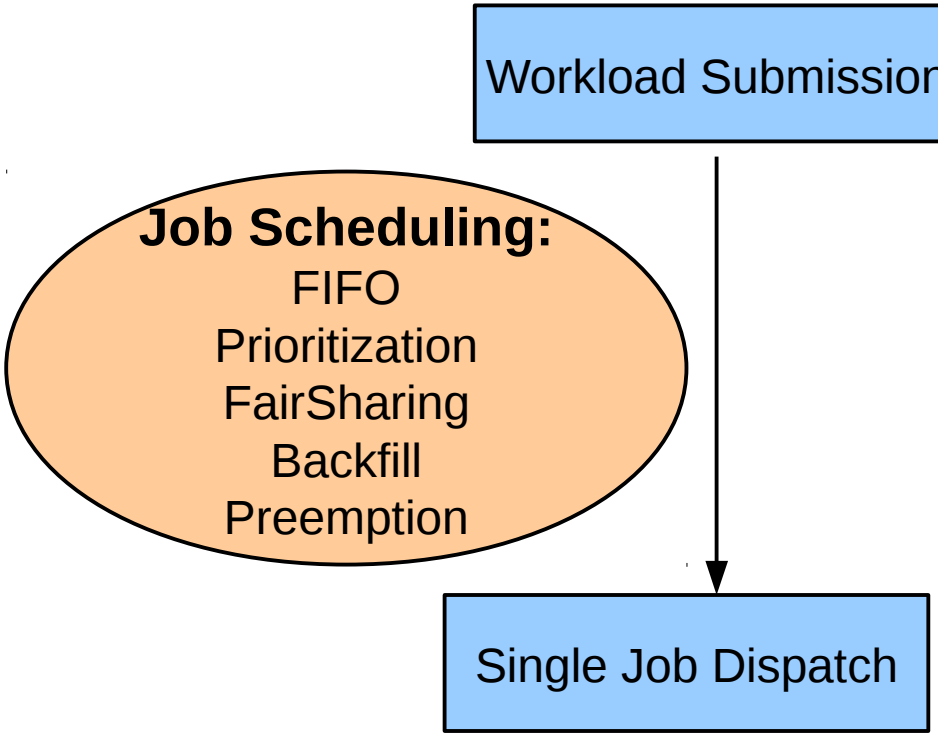
The syntax of this command is like:
**<type><REPORT><OPTIONS>** where <type> can be cluster, job or user and each type has various reports and options
Example1: sreport job sizesbyaccount
Example2: sreport cluster AccountUtilizationByUser
Example3: sreport user topusage account=gohn

```
Example:
>sreport cluster utilization
```

# SLURM scheduling / allocation procedures



# SLURM scheduling / allocation procedures



# SLURM Scheduling

- SLURM supports various **scheduling policies and optimization techniques** (non-exhaustive list) :
  - Backfill
  - Preemption
  - Fairsharing
- Advantage: Techniques can be **supported simultaneously**

# Multifactor Priority in SLURM

- Various **factors** can take part in the formula through the MultiFactor plugin:

  Job_priority =

  (PriorityWeightAge) * (age_factor) +

  (PriorityWeightFairshare) * (fair-share_factor) +

  (PriorityWeightJobSize) * (job_size_factor) +

  (PriorityWeightPartition) * (partition_factor)

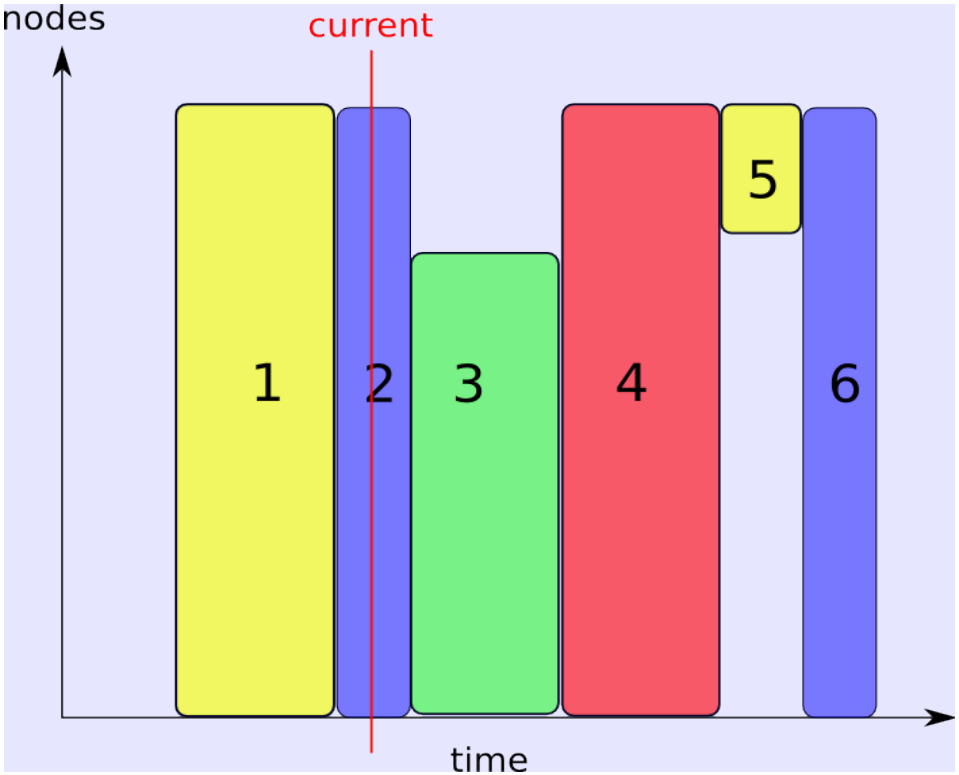
# Fairsharing in SLURM

- User and Group accounts created in the **database**
- **Inheritance** between Groups and Users for all the different characteristics (Fairshare factors, Max number of Jobs, Max number of CPUs, etc )
- Job Priorities based on the **CPU*Time utilization** of each user

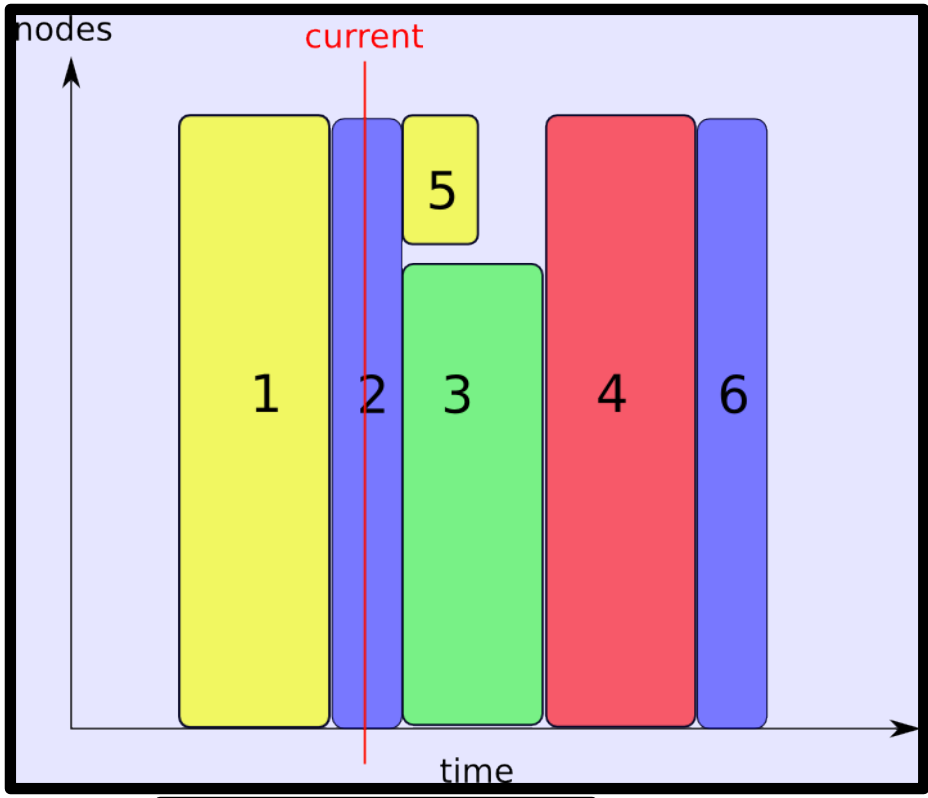
**Important Note:** To activate fairsharing in SLURM you need to add the Priority/multifactor parameter in slurm.conf along with the different parameters for the particular factors that are needed for the site

# Scheduling – Backfill

Holes can be filled if previous jobs order is not changed




FIFO Scheduler




Backfill Scheduler

# Scheduling Policies

**Scheduler Plugin Type**
**Sched/builtin** Default FIFO
**Sched/hold** variation on builtin; new jobs are held if /etc/slurm.hold file exists.

**Sched/backfill** schedule lower priority jobs as long as they don't delay a waiting higher priority job.

- Increases utilization of the cluster.
- Requires declaration of max execution time of lower priority jobs.
  - --time on 'srun',
  - DefaultTime or MaxTime on Partition
  - MaxWall from accounting association

```
#slurm.conf file
SchedulerType=sched/backfill
SchedulerParameters=defer,bf_interval=60
FastSchedule=1
```

# Scheduling Configuration Tips – Backfill

Important parameter for **backfill** to take effect is the **Walltime** of the job (Max time allowed for the job to be completed).

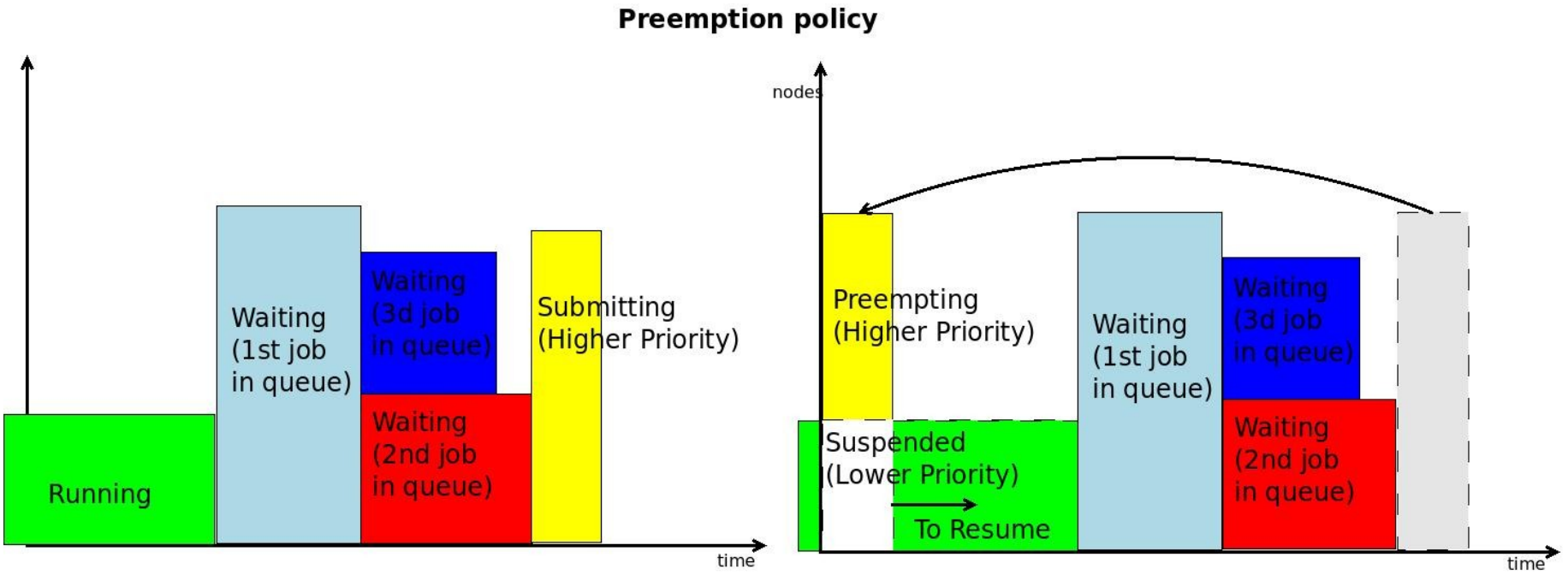
- Through command line option (--time=<Minutes>)
- Partitions or QOS can be declared with Walltime parameter and jobs submitted to these partitions inherit automatically those parameters.

Configuration of scheduler backfill in slurm.conf

Scheduler Parameters= bf_interval=#, bf_max_job_user=#,
bf_resolution=#,bf_window=#,max_job_bf=#

# Scheduling - Preemption

Preemption policy allows higher priority jobs to execute without waiting upon the cluster resources by taking the place of the lower priority jobs



# Preemption Policies

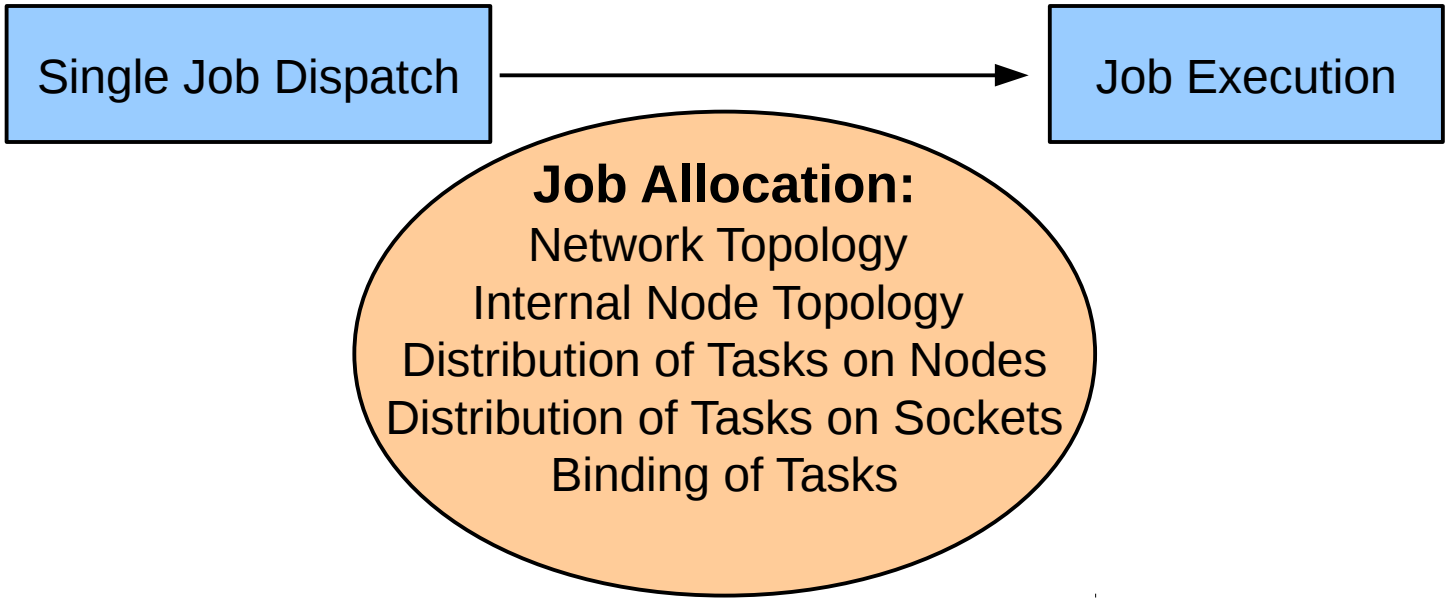
## Preempt Modes

**Cancel** preempted job is cancelled.
**Checkpoint** preempted job is checkpointed if possible, or cancelled.
**Gang** enables time slicing of jobs on the same resource.
**Requeue** job is requeued as restarted at the beginning (only for sbatch).
**Suspend** job is suspended until the higher priority job ends (requires Gang).

```
#slurm.conf file
PreemptMode=SUSPEND
PreemptType=preempt/qos
```

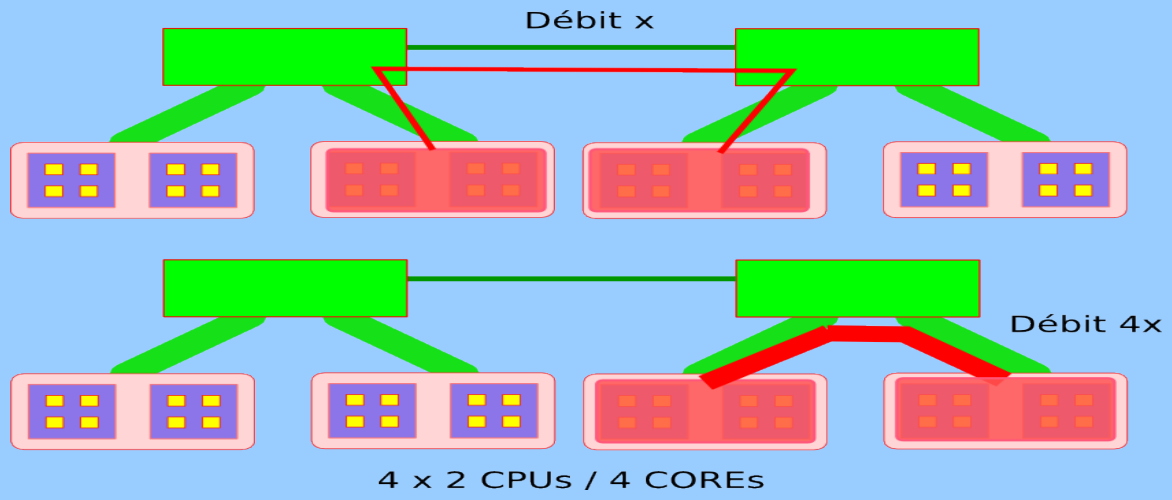
```
>sbatch -N3 ./sleep.sh 300
sbatch: Submitted batch job 489
>sbatch -p hiprio -N3 ./sleep.sh 20
sbatch: Submitted batch job 490
>squeue -Si
JOBID PARTITION  NAME   USER  ST   TIME  NODES NODELIST
 489   lowpri sleep.sh   user   S   0:06      1 n[12-14]
 490   hipri  sleep.sh   user   R   0:03      3 n[12-14]
```

# SLURM scheduling / allocation procedures



# Network Topology Aware Placement

- topology/tree SLURM Topology aware plugin. **Best-Fit** selection of resources
- In fat-tree hierarchical topology: Bisection Bandwidth Constraints need to be taken into account




```
#slurm.conf file
TopologyPlugin=topology/tree
```

# Configuration (topology.conf)

**topology.conf file** needs to exist on all computing nodes for network topology architecture description

```
# topology.conf file
SwitchName=Top
Switches=TS1,TS2,TS3,TS4,TS5,TS6,...

SwitchName=TS1 nodes=curie[1-18]
SwitchName=TS2 nodes=curie[19-37]
SwitchName=TS3 nodes=curie[38-56]
SwitchName=TS4 nodes=curie[57-75]
....
```

# Network Topology Aware Placement

**In the slurm.conf** the **topology/tree** plugin may be activated by the admins to allow job placement according to network topology constraints

**In the submission** commands the users may use the **--switches=<count>[@<max-time>]** parameter to indicate how many switches their job would be ideal to execute upon:

When a tree topology is used, this defines the maximum count of switches desired for the job allocation and optionally the maximum time to wait for that number of switches.

# Internal node topology/CPUs allocation procedure

SLURM uses four basic steps to manage CPU resources for a job/step:

**Step 1:** Selection of Nodes
**Step 2:** Allocation of CPUs from the selected Nodes
**Step 3:** Distribution of Tasks to the selected Nodes
**Step 4:** Optional Distribution and Binding of Tasks to CPUs within a Node

- SLURM provides a rich set of configuration and command line options to control each step
- Many options influence more than one step
- Interactions between options can be complex and difficult to predict
- Users may be constrained by Administrator's configuration choices

# Notable Options for Step 1: Selection of Nodes

Configuration options in **slurm.conf**

**Nodename**: Defines a node and its characteristics. This includes the layout of sockets, cores, threads and the number of logical CPUs on the node.

**FastSchedule**: Allows administrators to define “virtual” nodes with different layout of sockets, cores and threads and logical CPUs than the physical nodes in the cluster.

**PartitionName**: Defines a partition and its characteristics. This includes the set of nodes in the partition.

Command line options on **srun/salloc/sbatch** commands

**--partition, --nodelist**: Specifies the set of nodes from which the selection is made

**-N, --nodes**: Specifies the minimum/maximum number of nodes to be selected

**-B, --sockets-per-node, --cores-per-socket, --threads-per-core**: Limits node selection to nodes with the specified characteristics

# Notable Options for Step 2: Allocation of CPUs from Selected Nodes

Configuration options in **slurm.conf:**

**SelectType**:
**SelectType=select/linear**: Restricts allocation to whole nodes
**SelectType=select/cons_res**: Allows allocation of individual sockets, cores or threads as consumable resources

**SelectTypeParameters**: For select/cons_res, specifies the consumable resource type and default allocation method within nodes

Command line options on **srun/salloc/sbatch**:

**-n, --ntasks**: Specifies the number of tasks. This may affect the number of CPUs allocated to the job/step
**-c, --cpus-per-task**: Specifies the number of CPUs per task. This may affect the number of CPUs allocated to the job/step

# Notable Options for Step 3: Distribution of Tasks to Nodes

Configuration options in **slurm.conf**:

**MaxTasksPerNode**: Specifies maximum number of tasks per node

Command Line options on **srun/salloc/sbatch**:

**-m, --distribution**: Controls the order in which tasks are distributed to nodes.

# Notable Options for Step 4: Optional Distribution & Binding

Configuration options in **slurm.conf:**

**TaskPlugin**:
**TaskPlugin=task/none**: Disables this step.
**TaskPlugin=task/affinity**: Enables task binding using the task affinity plugin.
**TaskPlugin=task/cgroup**: Enables task binding using the new task cgroup plugin.

**TaskPluginParam**: For task/affinity, specifies the binding unit (sockets, cores or threads) and binding method (sched_setaffinity or cpusets)

Command Line options on **srun/salloc/sbatch**:

**--cpu_bind**: Controls many aspects of task affinity
**-m, --distribution**: Controls the order in which tasks are distributed to allocated CPUs on a node for binding

# Allocation & Distribution Methods

SLURM uses two default methods for allocating and distributing individual CPUs from a set of resources

- **block** method: Consume all eligible CPUs consecutively from a single resource before using the next resource in the set
- **cyclic** method: Consume eligible CPUs from each resource in the set consecutively in a round-robin fashion

The following slides illustrate the default method used by SLURM for each step.

# Allocation of Resources

Different ways of selecting resources in SLURM:

- Cyclic method (Balance between nodes / Round Robin )
- Block method (Minimization of fragmentation )

- **Cyclic**

```
[bench@wardlaw0 ~]$ srun -n10 -N2 –exclusive /bin/hostname
wardlaw67
wardlaw67
wardlaw67
wardlaw67
wardlaw67
wardlaw66
wardlaw66
wardlaw66
wardlaw66
wardlaw66
```

- **Block**

```
[bench@wardlaw0 ~]$ srun -n10 -N2 /bin/hostname
wardlaw67
wardlaw67
wardlaw67
wardlaw67
wardlaw67
wardlaw67
wardlaw67
wardlaw67
wardlaw67
wardlaw66
```

# Generic Resources (Allocation of GPUs, MIC, etc)

Generic Resources (GRES) are resources associated with a specific node that can be allocated to jobs and steps. The most obvious example of GRES use would be GPUs. GRES are identified by a specific name and use an optional plugin to provide device-specific support.

SLURM supports no generic resourses in the default configuration. One must explicitly specify which resources are to be managed in the **slurm.conf** configuration file. The configuration parameters of interest are:

- **GresTypes** a comma delimited list of generic resources to be managed (e.g. GresTypes=gpu,nic). This name may be that of an optional plugin providing additional control over the resources.
- **Gres** the specific generic resource and their count associated with each node (e.g. NodeName=linux[0-999] Gres=gpu:8,nic:2) specified on all nodes and SLURM will track the assignment of each specific resource on each node. Otherwise SLURM will only track a count of allocated resources rather than the state of each individual device file.

# Generic Resources (Allocation of GPUs, MIC, etc)

**For configuration** the new file **gres.conf** needs to exist on each compute node with gres resources

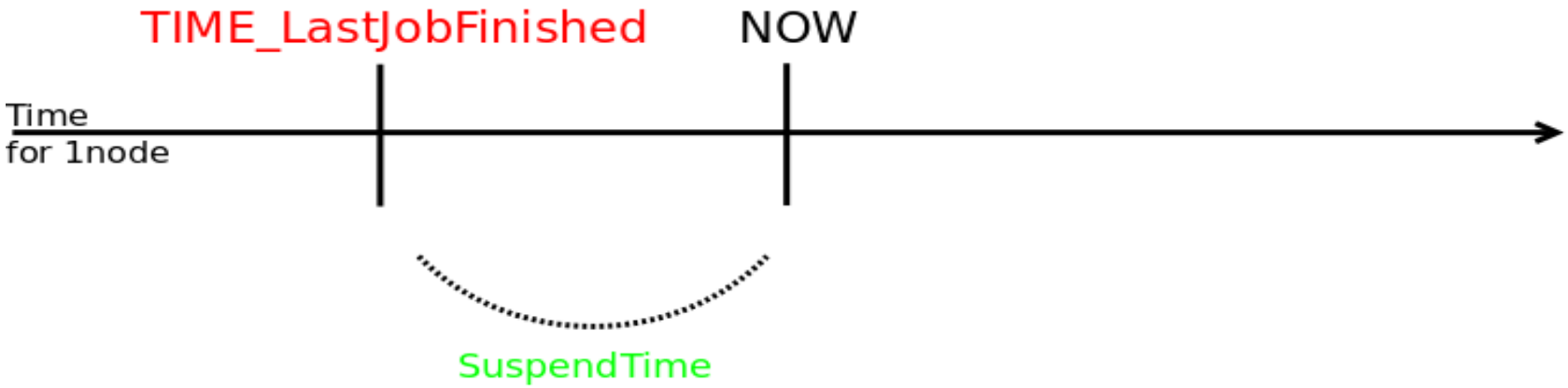
```
# Configure support for our four GPUs
Name=gpu File=/dev/nvidia0 CPUs=0,1
Name=gpu File=/dev/nvidia1 CPUs=0,1
Name=gpu File=/dev/nvidia2 CPUs=2,3
Name=gpu File=/dev/nvidia3 CPUs=2,3
```

**For job execution** the –gres option has to be used for to salloc, sbatch, and srun.

**--gres=<list>**Specifies a comma delimited list of generic consumableresources. The format of each entry on the list is**"name[:count]".**

# Energy reduction techniques

- Parameters for energy reduction techniques
- Automatic node shut-down or other actions in case of resources **unutilization** during particular time.




Algorithm for SLURM Energy Reduction Techniques

```
Nodes Sleep Actions
        if    SuspendTime > A_PreDefined_Idle_TIME
                exec SuspendProgram upon SuspendRate nodes per minute


Nodes WakeUp Actions
        if    SleepingNode_isNeeded  then
                exec ResumeProgram upon ResumeRate nodes per minute
```

# Energy reduction techniques Configuration

**SuspendTime:** Idle time to activate energy reduction techniques. A negative number disables power saving mode. The default value is -1 (disabled).

**SuspendRate:** # nodes added per minute. A value of zero results in no limits being imposed. The default value is 60. Use this to prevent rapid drops in power consumption.

**ResumeRate:** # nodes removed per minute. A value of zero results in no limits being imposed. The default value is 300. Use this to prevent rapid increases in power consumption.

**SuspendProgram:** Program to be executed to place nodes into power saving mode. The program executes as SlurmUser (as configured in slurm.conf). The argument to the program will be the names of nodes to be placed into power savings mode (using Slurm's hostlist expression format).

**ResumeProgram:** This program may use the scontrol show node command to insure that a node has booted and the slurmd daemon started.

**SuspendTimeout, ResumeTimeout, SuspendExcNodes,SuspendExcParts, BatchStartTimeout**

# Using different MPI libraries

**OpenMPI**

The system administrator must specify the range of ports to be reserved in the slurm.conf file using the MpiParams parameter. For example:

```
MpiParams=ports=12000-12999
```

Launch tasks using the srun command plus the option --resv-ports.

Alternately define the environment variable SLURM_RESV_PORT

```
srun –resv-ports -n <num_procs> a.out
```

If OpenMPI is configured with --with-pmi either pmi or pmi2 the OMPI jobs can be launched directly using the srun command. This is the preferred way. If the pmi2 support is enabled then the command line options '--mpi=pmi2' has to be specified on the srun command line.

```
srun --mpi=pmi2 -n <num_procs> a.out
```

**Intel-MPI**

Set the *I_MPI_PMI_LIBRARY* environment variable to point to the SLURM Process Management Interface (PMI) library:

```
export I_MPI_PMI_LIBRARY=/path/to/slurm/pmi/library/libpmi.so
```

Use the *srun* command to launch the MPI job:

```
srun -n <num_procs> a.out
```

# Hands-On Exercises
# Accounting/QOS/Limitations

**Exercise 9:**Activate accounting using slurmdbd and mysql
-configure 3 users with different limitations on maximum allowed jobs
-and 2 QOS with different priorities and walltimes

1.Usage of sacctmgr command as root
2.Create an account for each user with *sacctmgr create account*
3.Update accounts including the limitations on maximum allowed jobs with sacctmgr update account name=x set GrpJobs=y
4.Create a QOS with sacctmgr create qos

# Hands-On Exercises
# Scheduling

**Exercise 10:**Activate :
-backfill scheduling and consider high throughput workloads
-multifactor with priority on smaller jobs
-preemption on the QOS level

**11)** Create a backfill scenario where a small job will be running and a large job will demand all the resources and then the following jobs will be blocked and waiting for the large one to be executed. Set the walltime to your Job in order to see backfilling take place.

**12)** Create a preemption scenario where a high priority job will kill a low priority one and requeue it.

# Allocation-Placement

**Exercise 13:**Activate :
-network topology aware scheduling
-internal node topology with possibilities to deal with memory and cores as seperate resources
-CPU binding

# Power Management

**Exercise 14:** Activate :
-power management in a way that when nodes are idle for more than 10min they are turned off
-node power monitoring
-experiment with real MPI application

- Part 1: Basics
  - Overview, Architecture, Configuration files, Partitions, Plugins, Reservations
- Part 2: Advanced Configuration
  - Accounting, Scheduling, Allocation, Network Topology Placement, Generic Resources Management, Energy Reduction Techniques
- **Part 3: Experts Configuration**
  - **Isolation with cgroups, Power Management, Simulation and evaluation**

Bull
atos technologies

# Advantages: cgroups support for HPC

- To guarantee that every consumed resources is consumed the way it's planned to be
  - leveraging Linux latest features in terms of process control and resource management
  - Enabling node sharing
- While enhancing the connection with Linux systems
  - Improve **tasks isolation** upon resources
  - Improve **efficiency** of resource management activities (e.g., process tracking, collection of accounting statistics)
  - Improve **robustness** (e.g. more reliable cleanup of jobs)
- And simplifying the addition of **new controlled resources and features**
  - prospective management of network and I/O as individual resources

# Introduction to cgroups

Control Groups (cgroups) is a **Linux kernel mechanism** (appeared in 2.6.24) to limit, isolate and monitor resource usage (CPU, memory, disk I/O, etc.) of groups of processes.

**Features**

- ***Resource Limiting*** (i.e. not to exceed a memory limit)
- ***Prioritization*** (i.e. groups may have larger share of CPU)
- ***Isolation*** (i.e. isolate GPUs for particular processes)
- ***Accounting*** (i.e. montior resource usage for processes)
- ***Control*** (i.e. suspending and resuming processes)

# Cgroups subsystems

- **cpuset** – assigns tasks to individual CPUs and memory nodes in a cgroup
- **cpu** – schedules CPU access to cgroups
- **cpuacct** – reports CPU resource usage of tasks of a cgroup
- **memory** – set limits on memory use and reports memory usage for a cgroup
- **devices** – allows or denies access to devices (i.e. gpus) for tasks of a cgroup
- **freezer** – suspends and resumes tasks in a cgroup
- **net_cls** – tags network packets in a cgroup to allow network traffic priorities
- **ns** – namespace subsystem
- **blkio** – tracks I/O ownership, allowing control of access to block I/O resources

# Cgroups functionality rules

- Cgroups are represented as **virtual file systems**
  - Hierarchies are directories, created by mounting subsystems, using the mount command; subsystem names specified as mount options
  - Subsystem parameters are represented as files in each hierarchy with values that apply only to that cgroup
- **Interaction with cgroups** take place by manipulating directories and files in the cgroup virtual file system using standard shell commands and system calls (mkdir, mount, echo, etc)
  - *tasks* file in each cgroup directory lists the tasks (pids) in that cgroup
  - Tasks are automatically removed from a cgroup when they terminate or are added to a different cgroup in the same hierarchy
  - Each task is present in only one cgroup in each hierarchy
- Cgroups have a mechanism for **automatic removal** of abandoned cgroups (release_agent)

# Cgroups subsystems parameters

cpuset subsystem

**cpuset.cpus**: defines the set of cpus that the tasks in the cgroup are allowed to execute on

**cpuset.mems**: defines the set of memory zones that the tasks in the cgroup are allowed to use

memory subsystem

**memory.limit_in_bytes**: defines the memory limit for the tasks in the cgroup

**memory.swappiness**: controls kernel reclamation of memory from the tasks in the cgroup (swap priority)

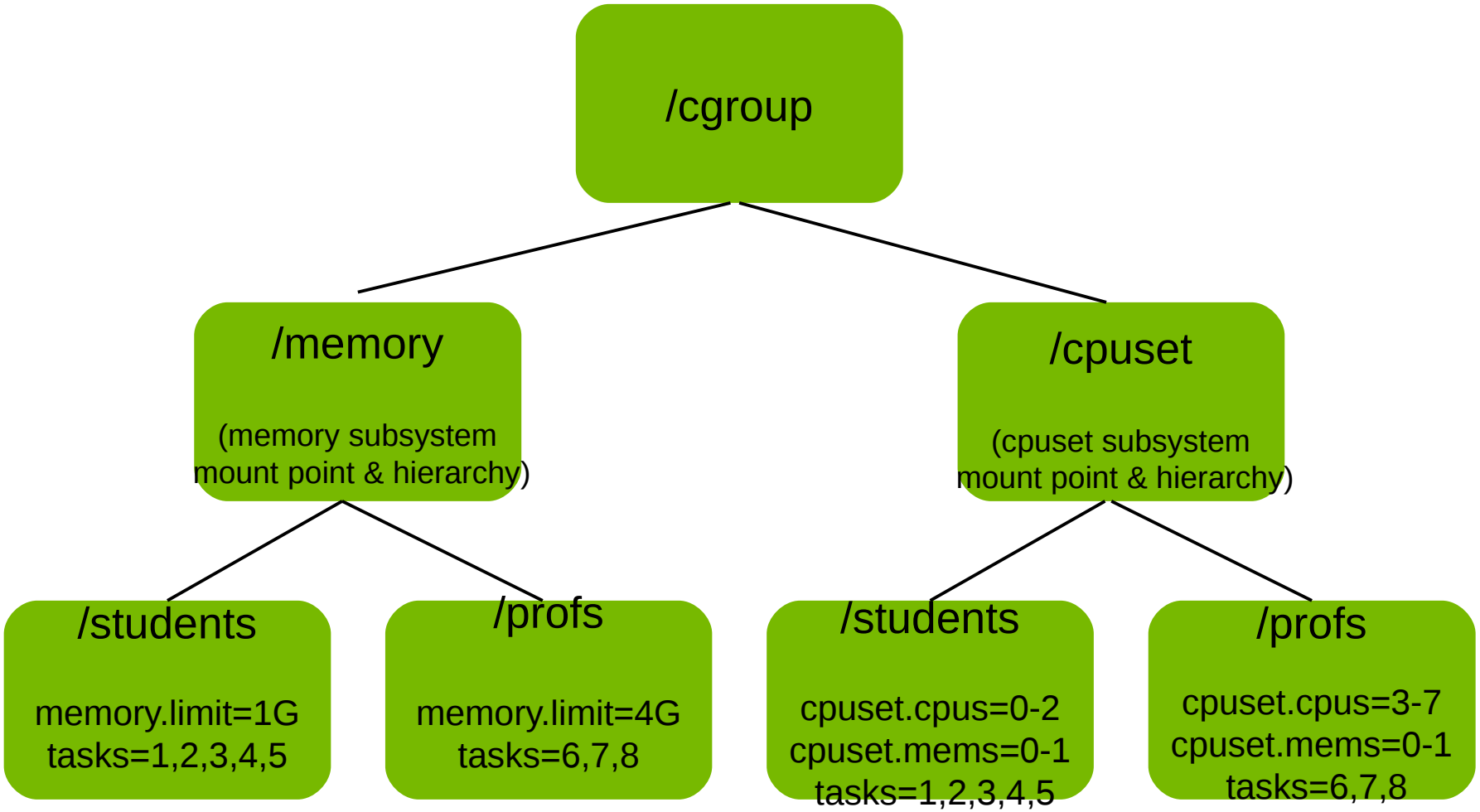
freezer subsystem

**freezer.state**: controls whether tasks in the cgroup are active (runnable) or suspended

devices subsystem

**devices_allow**: specifies devices to which tasks in a cgroup have acces

# Cgroups functionality example



# Cgroups functionality example

```
[root@mordor:~]# mkdir /cgroup
[root@mordor:~]# mkdir /cgroup/cpuset
[root@mordor:~]# mount -t cgroup -o cpuset none /cgroup/cpuset
[root@mordor:~]# ls /cgroup/cpuset/
cpuset.cpus  cpuset.mems tasks notify_on_release release_agent
[root@mordor:~]# mkdir /cgroup/cpuset/students
[root@mordor:~]# mkdir /cgroup/cpuset/profs
[root@mordor:~]# echo 0-2 > /cgroup/cpuset/students/cpuset.cpus
[root@mordor:~]# echo 0 > /cgroup/cpuset/students/cpuset.mems
[root@mordor:~]# echo $PIDS_st > /cgroup/cpuset/students/tasks
[root@mordor:~]# echo 3-7 > /cgroup/cpuset/profs/cpuset.cpus
[root@mordor:~]# echo 1 > /cgroup/cpuset/profs/cpuset.mems
[root@mordor:~]# echo $PIDS_pr > /cgroup/cpuset/profs/tasks
```

# Process Tracking with Cgroups

## Track job processes using the freezer subsystem

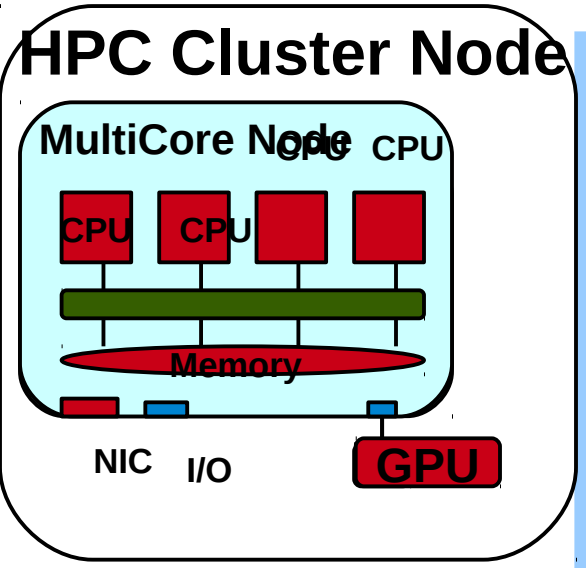
- Every spawned process is tracked
  - Automatic inheritance of parent's cgroup
  - No way to escape the container
- Every processes can be frozen
  - Using the Thawed|Frozen state of the subsystem
  - No way to avoid the freeze action

# Cgroup **Proctrack** plugin: **freezer** subsystem

## [mat@leaf slurm]$ srun  sleep 300

```
[root@leaf ~]# cat /cgroup/freezer/uid_500/job_53/step_0/freezer.state
THAWED
[root@leaf ~]# scontrol suspend 53
[root@leaf ~]# ps -ef f | tail -n 2
root     15144     1  0 17:10 ?        Sl     0:00 slurmstepd: [53.0]
mat      15147 15144  0 17:10 ?        T      0:00  \_ /bin/sleep 300
[root@leaf ~]# cat /cgroup/freezer/uid_500/job_53/step_0/freezer.state
FREEZING
[root@leaf ~]# scontrol resume 53
[root@leaf ~]# ps -ef f | tail -n 2
root     15144     1  0 17:10 ?        Sl     0:00 slurmstepd: [53.0]
mat      15147 15144  0 17:10 ?        S      0:00  \_ /bin/sleep 300
[root@leaf ~]# cat /cgroup/freezer/uid_500/job_53/step_0/freezer.state
THAWED
[root@leaf ~]#
```

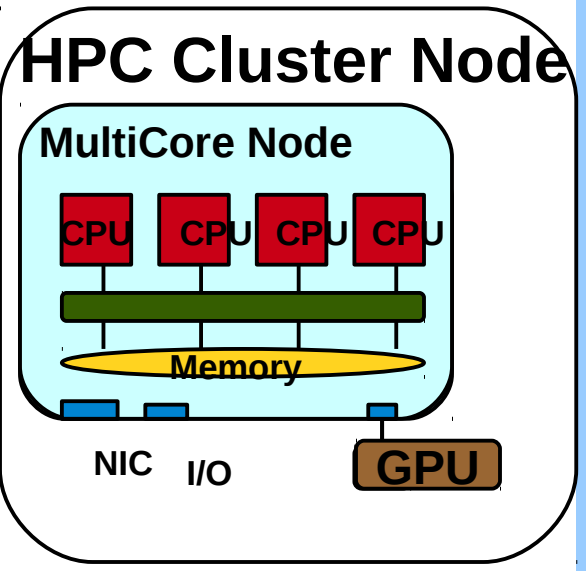
# Task confinement for allocated resources




## Constrain jobs tasks to the allocated resources

- 3 independant layers of managed resources using 3 subsystems
  - Cores (**cpuset**), Memory (**memory**), GRES (**devices**)
- Every spawned process is tracked
  - Automatic inheritance of parent's cgroup
  - No escape, no way to use additional resources,
- Each layer has its own additional parameters
- More resources could be added in the future

# Task confinement for cpus




## Constrain jobs tasks to the allocated cores

- Configurable feature
  - ConstrainCores=yes|no
- Use step's allocated cores with “exclusive steps”
  - Otherwise, let steps use job's allocated cores
- Basic affinity management as a configurable sub-feature
  - TaskAffinity=yes|no in cgroup.conf (rely on HWLOC)
  - Automatic block and cyclic distribution of tasks

# Cgroup **Task** plugin : **cpuset** subsystem

```
[mat@leaf slurm]$ salloc --exclusive srun -n1 --cpu_bind=none sleep
 3000
salloc: Granted job allocation 55
```

```
 [root@leaf ~]# egrep "Cores|Affinity" /etc/slurm/cgroup.conf
ConstrainCores=yes
TaskAffinity=yes
[root@leaf ~]# tail -f /var/log/slurmd.leaf10.log |grep task/cgroup
[2011-09-16T17:24:59] [55.0] task/cgroup: now constraining jobs allocated
 cores
[2011-09-16T17:24:59] [55.0] task/cgroup: loaded
[2011-09-16T17:24:59] [55.0] task/cgroup: job abstract cores are '0-31'
[2011-09-16T17:24:59] [55.0] task/cgroup: step abstract cores are '0-31'
[2011-09-16T17:24:59] [55.0] task/cgroup: job physical cores are '0-31'
[2011-09-16T17:24:59] [55.0] task/cgroup: step physical cores are '0-31'
[2011-09-16T17:24:59] [55.0] task/cgroup: task[0] is requesting no affinity
```

# Cgroup **Task** plugin : **cpuset** subsystem

```
[mat@leaf slurm]$ salloc --exclusive srun -n1 --cpu_bind=cores sleep 3000
salloc: Granted job allocation 57
```

```
 [root@leaf ~]# egrep "Cores|Affinity" /etc/slurm/cgroup.conf
ConstrainCores=yes
TaskAffinity=yes
[root@leaf ~]# tail -f /var/log/slurmd.leaf10.log |grep task/cgroup
[2011-09-16T17:31:17] [57.0] task/cgroup: now constraining jobs allocated cores
[2011-09-16T17:31:17] [57.0] task/cgroup: loaded
[2011-09-16T17:31:17] [57.0] task/cgroup: job abstract cores are '0-31'
[2011-09-16T17:31:17] [57.0] task/cgroup: step abstract cores are '0-31'
[2011-09-16T17:31:17] [57.0] task/cgroup: job physical cores are '0-31'
[2011-09-16T17:31:17] [57.0] task/cgroup: step physical cores are '0-31'
[2011-09-16T17:31:17] [57.0] task/cgroup: task[0] is requesting core level binding
[2011-09-16T17:31:17] [57.0] task/cgroup: task[0] using Core granularity
[2011-09-16T17:31:17] [57.0] task/cgroup: task[0] taskset '0x00000001' is set
```

# Cgroup **Task** plugin : **cpuset** subsystem

```
[mat@leaf slurm]$ salloc --exclusive srun -n1 --cpu_bind=socket sleep 3000
salloc: Granted job allocation 58
```

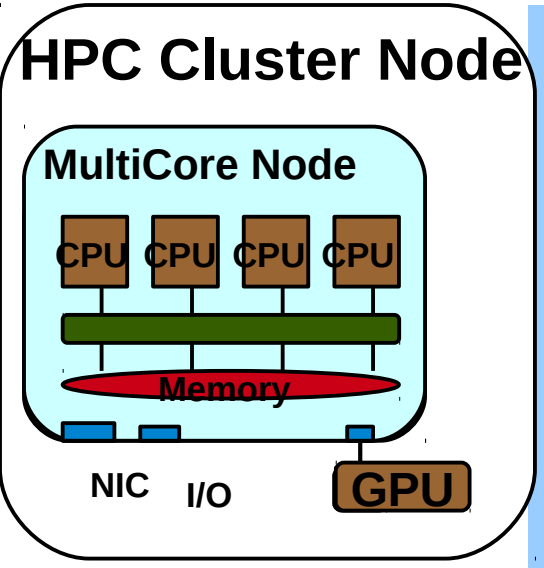
```
 [root@leaf ~]# egrep "Cores|Affinity" /etc/slurm/cgroup.conf
ConstrainCores=yes
TaskAffinity=yes
[root@leaf ~]# tail -f /var/log/slurmd.leaf10.log |grep task/cgroup
[2011-09-16T17:33:31] [58.0] task/cgroup: now constraining jobs allocated cores
[2011-09-16T17:33:31] [58.0] task/cgroup: loaded
[2011-09-16T17:33:31] [58.0] task/cgroup: job abstract cores are '0-31'
[2011-09-16T17:33:31] [58.0] task/cgroup: step abstract cores are '0-31'
[2011-09-16T17:33:31] [58.0] task/cgroup: job physical cores are '0-31'
[2011-09-16T17:33:31] [58.0] task/cgroup: step physical cores are '0-31'
[2011-09-16T17:33:31] [58.0] task/cgroup: task[0] is requesting socket level binding
[2011-09-16T17:33:31] [58.0] task/cgroup: task[0] using Socket granularity
[2011-09-16T17:33:31] [58.0] task/cgroup: task[0] taskset '0x00000003' is set
```

# Cgroup **Task** plugin : **cpuset** subsystem

[mat@leaf slurm]$ salloc --exclusive srun -n2 --cpu_bind=socket sleep 3000
salloc: Granted job allocation 60

```
 [root@leaf ~]# egrep "Cores|Affinity" /etc/slurm/cgroup.conf
ConstrainCores=yes
TaskAffinity=yes
[root@leaf ~]# tail -f /var/log/slurmd.leaf10.log |grep task/cgroup[2011-09-16T17:36:18] [60.0]
 task/cgroup: now constraining jobs allocated cores
[2011-09-16T17:36:18] [60.0] task/cgroup: loaded
[2011-09-16T17:36:18] [60.0] task/cgroup: job abstract cores are '0-31'
[2011-09-16T17:36:18] [60.0] task/cgroup: step abstract cores are '0-31'
[2011-09-16T17:36:18] [60.0] task/cgroup: job physical cores are '0-31'
[2011-09-16T17:36:18] [60.0] task/cgroup: step physical cores are '0-31'
[2011-09-16T17:36:18] [60.0] task/cgroup: task[0] is requesting socket level binding
[2011-09-16T17:36:18] [60.0] task/cgroup: task[1] is requesting socket level binding
[2011-09-16T17:36:18] [60.0] task/cgroup: task[1] using Core granularity
[2011-09-16T17:36:18] [60.0] task/cgroup: task[1] higher level Socket found
[2011-09-16T17:36:18] [60.0] task/cgroup: task[1] taskset '0x00000003' is set
[2011-09-16T17:36:18] [60.0] task/cgroup: task[0] using Core granularity
[2011-09-16T17:36:18] [60.0] task/cgroup: task[0] higher level Socket found
[2011-09-16T17:36:18] [60.0] task/cgroup: task[0] taskset '0x00000003' is set
```

# Task confinement for memory : **memory** subsystem




## Constrain jobs tasks to the allocated amount of memory

- Configurable feature
  - ConstrainRAMSpace=yes|no
  - ConstrainSwapSpace=yes|no
- Use step's allocated amount of memory with “exclusive steps”
  - Else, let steps use job's allocated amount
- Both RSS and swap are monitored
- Trigger OOM killer on the cgroup's tasks when reaching limits
- Tolerant mechanism
  - AllowedRAMSpace , AllowedSwapSpace percents

# Cgroup **Task** plugin : **memory** subsystem

```
[mat@leaf slurm]$ salloc --exclusive --mem-per-cpu 100 srun -n1 sleep 3000
salloc: Granted job allocation 67
```

```
[root@leaf ~]# tail -f /var/log/slurmd.leaf10.log |grep task/cgroup
[2011-09-16T17:55:20] [67.0] task/cgroup: now constraining jobs allocated memory
[2011-09-16T17:55:20] [67.0] task/cgroup: loaded
[2011-09-16T17:55:20] [67.0] task/cgroup: job mem.limit=3520MB memsw.limit=3840MB
[2011-09-16T17:55:20] [67.0] task/cgroup: step mem.limit=3520MB memsw.limit=3840MB
```

```
[mat@leaf slurm]$ salloc --exclusive --mem-per-cpu 100 srun –
 exclusive -n1 sleep 3000
salloc: Granted job allocation 68
```

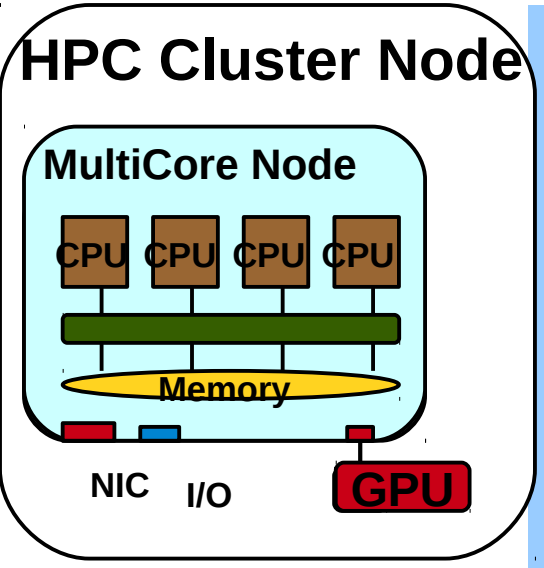
```
[root@leaf ~]# tail -f /var/log/slurmd.leaf10.log |grep task/cgroup
[2011-09-16T17:57:31] [68.0] task/cgroup: now constraining jobs allocated memory
[2011-09-16T17:57:31] [68.0] task/cgroup: loaded
[2011-09-16T17:57:31] [68.0] task/cgroup: job mem.limit=3520MB memsw.limit=3840MB
[2011-09-16T17:57:31] [68.0] task/cgroup: step mem.limit=110MB memsw.limit=120MB
```

# Cgroup **Task** plugin : **memory** subsystem OOM killer usage

```
[mat@leaf slurm]$ salloc --exclusive --mem-per-cpu 100 srun -n1 sleep
 3000
salloc: Granted job allocation 67
```

```
slurmd[berlin27]: Step 268.0 exceeded 1310720 KB
memory limit, being killed

srun: Exceeded job memory limit

srun: Job step aborted: Waiting up to 2 seconds for job step
to finish.

slurmd[berlin27]: *** STEP 268.0 KILLED AT 2012-03-
31T15:50:36 WITH SIGNAL 9 ***

srun: error: berlin27: tasks 0,1: Killed
```

# Tasks confinement for devices: **devices** subsystem




## Constrain jobs tasks to the allocated system devices

- Based on the **GRES** plugin for generic resources allocation (NIC, GPUs, etc) and built upon the cgroup task plugin
  - Each task is allowed to access to a number of devices by default
  - Only the tasks that have granted allocation on the **GRES** devices will be allowed to have access on them.
  - Tasks with no granted allocation upon **GRES** devices will not be able to use them.

## Cgroup Devices Configuration Example

```
[root@mordor cgroup]# egrep "Devices" /etc/slurm/cgroup.conf
ConstrainDevices=yes
AllowedDevicesFile="/etc/slurm/allowed_devices.conf"
```

```
[root@mordor cgroup]# cat /etc/slurm/allowed_devices.conf
/dev/sda*
/dev/null
/dev/zero
/dev/urandom
/dev/cpu/*/*
```

# Cgroup **Task** plugin : **devices** subsystem

**Cgroup Devices Logic as implemented in task plugin**

**1)** Initialization phase (information collection gres.conf file, major, minor, etc)

**2)** Allow all devices that should be allowed by default (allowed_devices.conf)

**3)** Lookup which gres devices are allocated for the job

- Write allowed gres devices to devices.allow file
- Write denied gres devices to devices.deny file

**4)** Execute **2** and **3** for job and steps tasks (different hierarchy level in cgroups)

# Cgroups **devices** subsystem : Usage Example

```
[root@mordor cgroup]# egrep "Gres" /etc/slurm/slurm.conf
GresTypes=gpu
NodeName=cuzco[57,61] Gres=gpu:2 Procs=8 Sockets=2 CoresPerSocket=4
```

```
[root@cuzco51]# cat /etc/slurm/allowed_devices.conf
/dev/sda*
/dev/null
```

```
[gohn@cuzco0]$ cat gpu_test.sh
#!/bin/sh
sleep 10
echo 0 > /dev/nvidia0
echo 0 > /dev/nvidia1
```

# Cgroups **devices** subsystem : Usage Example

```
[gohn@cuzco0]$ srun -n1 –gres=gpu:1 -o output ./gpu_test.sh
```

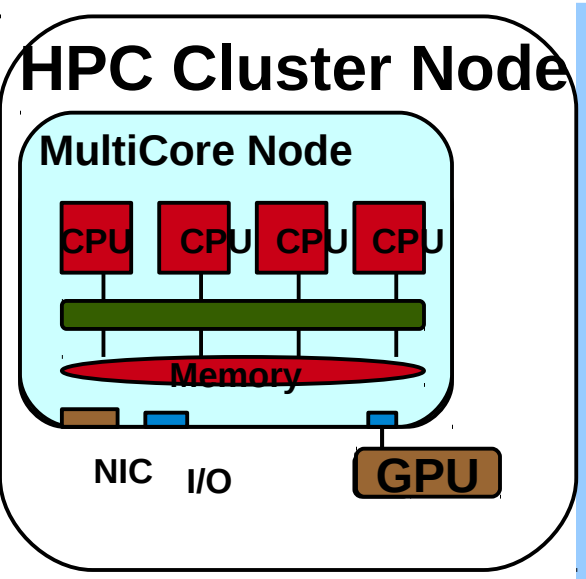
```
[root@cuzco51 ~]# tail -f /var/log/slurmd.cuzco51.log
[2011-09-20T03:10:02] [22.0] task/cgroup: manage devices jor job '22'
[2011-09-20T03:10:02] [22.0] device : /dev/nvidia0 major 195, minor 0
[2011-09-20T03:10:02] [22.0] device : /dev/nvidia1 major 195, minor 1
[2011-09-20T03:10:02] [22.0] device : /dev/sda2 major 8, minor 2
[2011-09-20T03:10:02] [22.0] device : /dev/sda1 major 8, minor 1
[2011-09-20T03:10:02] [22.0] device : /dev/sda major 8, minor 0
[2011-09-20T03:10:02] [22.0] device : /dev/null major 1, minor 3
[2011-09-20T03:10:02] [22.0] Default access allowed to device b 8:2 rwm
[2011-09-20T03:10:02] [22.0] parameter 'devices.allow' set to 'b 8:2 rwm' for '/cgroup/devices/uid_50071/job_22/step_0'
[2011-09-20T03:10:02] [22.0] Default access allowed to device b 8:1 rwm
[2011-09-20T03:10:02] [22.0] parameter 'devices.allow' set to 'b 8:1 rwm' for '/cgroup/devices/uid_50071/job_22/step_0'
[2011-09-20T03:10:02] [22.0] Default access allowed to device b 8:0 rwm
[2011-09-20T03:10:02] [22.0] parameter 'devices.allow' set to 'b 8:0 rwm' for '/cgroup/devices/uid_50071/job_22/step_0'
[2011-09-20T03:10:02] [22.0] Default access allowed to device c 1:3 rwm
[2011-09-20T03:10:02] [22.0] parameter 'devices.allow' set to 'c 1:3 rwm' for '/cgroup/devices/uid_50071/job_22/step_0'
[2011-09-20T03:10:02] [22.0] Allowing access to device c 195:0 rwm
[2011-09-20T03:10:02] [22.0] parameter 'devices.allow' set to 'c 195:0 rwm' for '/cgroup/devices/uid_50071/job_22/step_0'
[2011-09-20T03:10:02] [22.0] Not allowing access to device c 195:1 rwm
[2011-09-20T03:10:02] [22.0] parameter 'devices.deny' set to 'c 195:1 rwm' for '/cgroup/devices/uid_50071/job_22/step_0'
```

# Cgroups **devices** subsystem : Usage Example

```
[root@cuzco51 ~]# cat /cgroup/devices/uid_50071/job_22/step_0/tasks
4875
4879
4882
[root@cuzco51 ~]# cat /cgroup/devices/uid_50071/job_22/step_0/devices.list
b 8:2 rwm
b 8:1 rwm
b 8:0 rwm
c 1:3 rwm
c 195:0 rwm
```

```
[gohn@cuzco0]$ cat output
/home/GPU/./gputest.sh: line 4: echo: write error: Invalid argument
/home/GPU/./gputest.sh: line 5: /dev/nvidia1: Operation not
  permitted
```

# Monitoring Resource Usage: **cpuacct** and **memory subsystems**




## Monitoring cpu usage with cpuacct subsystem and memory usage with memory subsystem

- Implemented as a jobacct_gather plugin for SLURM
- Collects information concerning CPU time and Memory RSS consumed for each task of the cgroup
- Values reported as a new job characteristics in the accounting database of SLURM
- Values can be used for billing purposes
- Monitor per job energy consumption (not through cgroups )

# Monitoring Resources:
# **cpuacct -memory** subsystems

```
[gohn@cuzco0]$ srun -n32  ./malloc
[gohn@cuzco0]$ sacct -j 167
```

```
       JobID    JobName Partition  MaxRSS   AveRSS   MaxPages  AvePages
MinCPU      AveCPU  Elapsed  State  Ntasks  AllocCPUs  ExitCode

------------ ---------- ------------- ------------- ---------- ---------- ----------
----------

     167.0    malloc  shared  61311K   57221K   239.24G  99893120K
 00:03.000    00:03.000  00:01:10  COMPLETED  32  32  0.0
```

# Cgroup **Task** plugin : **devices** subsystem

**Cgroup Devices Logic as implemented in task plugin**

**1)** Initialization phase (information collection gres.conf file, major, minor, etc)

**2)** Allow all devices that should be allowed by default (allowed_devices.conf)

**3)** Lookup which gres devices are allocated for the job

- Write allowed gres devices to devices.allow file
- Write denied gres devices to devices.deny file

**4)** Execute **2** and **3** for job and steps tasks (different hierarchy level in cgroups)

# Energy accounting and control

# Summary of the energy accounting and control features

- Power and Energy consumption monitoring per node level.
- Energy consumption accounting per step/job on SLURM DataBase
- Power profiling per step/job on the end of job
- Frequency Selection Mechanisms for user control of job energy consumption

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**How this takes place:**

- Dedicated Plugins for Support of in-band collection of energy/power data (IPMI / RAPL)
- Dedicated Plugins for Support of out-of-band collection of energy/power data (RRD databases )
- Power data job profiling with HDF5 file format
- SLURM Internal power-to-energy and energy-to-power calculations

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•**Overhead:** In-band Collection
•**Precision:** of the measurements and internal calculations
•**Scalability:** Out-of band Collection

**How thi**

- Dedicated
energy/po
- Dedicated Plugins for Support of out-of-band collection of energy/power data (RRD databases )
- Power data job profiling with HDF5 file format
- SLURM Internal power-to-energy and energy-to-power calculations

# In-band collection of power/energy data with IPMI

- **IPMI** is a message-based, hardware-level interface specification (may operate in-band or out-of-band)
- Communication with the Baseboard Management Controller BMC which is a specialized microcontroller embedded on the motherboard of a computer
- SLURM support is based on the FreeIPMI API:

  http://www.gnu.org/software/freeipmi/
  - FreeIPMI includes a userspace driver that works on most motherboards without any required driver.
  - No thread interferes with application execution
- The data collected from IPMI are currently instantaneous measures in Watts
- SLURM individual polling frequency (>=1sec)
  - direct usage for power profiling
  - but internal SLURM calculations for energy reporting per job

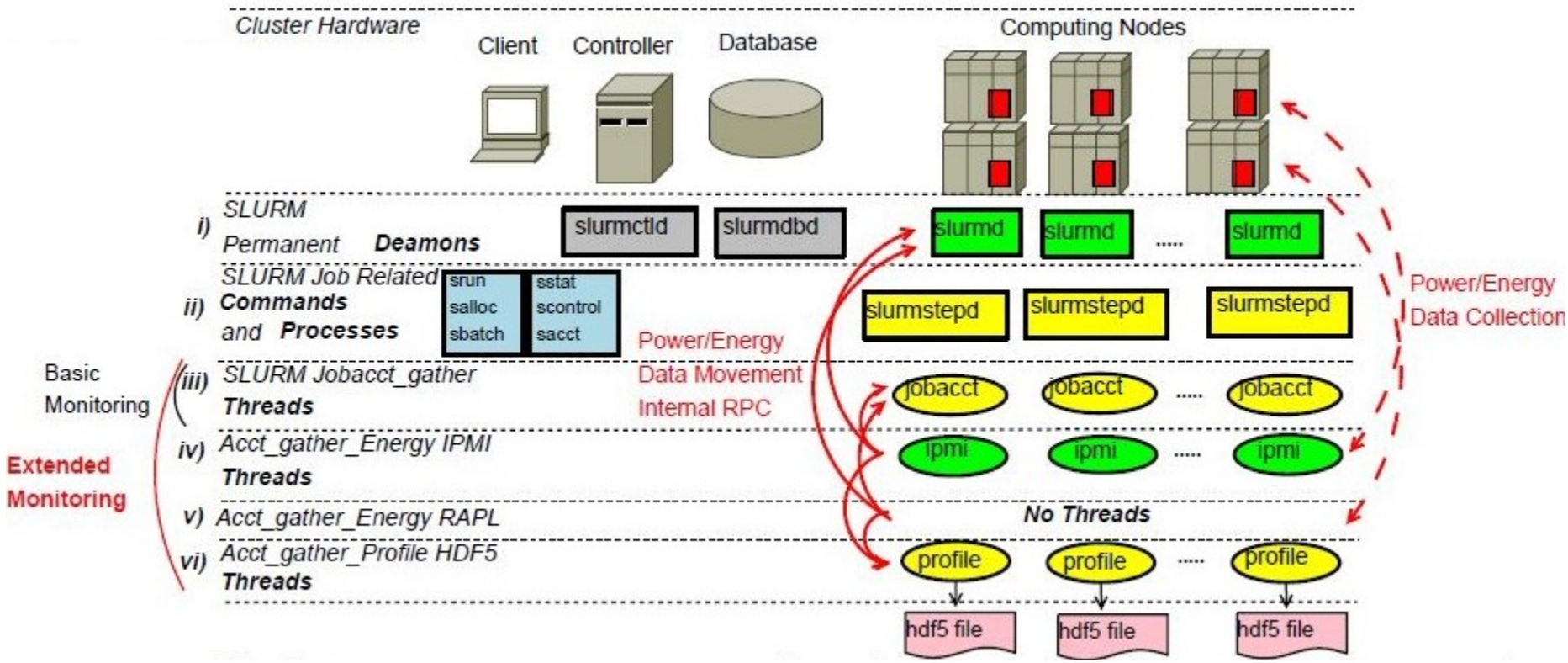
# In-band collection of power/energy data with RAPL

- **RAPL** ( Running Average Power Limit) are particular interfaces on Intel Sandy Bridge processors (and later models) implemented to provide a mechanism for keeping the processors in a particular user-specified power envelope.
- Interfaces can estimate current energy usage based on a software model driven by hardware performance counters, temperature and leakage models
  - Linux supports an ’MSR’ driver and access to the register can be made through /dev/cpu/*/msr with priviledged read permissions
- The data collected from RAPL is energy consumption in Joules (since the last boot of the machine)
- SLURM individual polling frequency (>=1sec)
  - direct usage for energy reporting per job
  - but internal SLURM calculations for power reporting

# Power Profiling

- Job profiling to periodically capture the task's usage of various resources like CPU, Memory, Lustre, Infiniband and Power per node
- Resource Independent polling frequency configuration
- Based on **hdf5** file format http://www.hdfgroup.org opensource software library
  - versatile data model that can represent very complex data objects and a wide variety of metadata
  - portable file format with no limit on the number or size of data objects stored
- Profiling per node (one hdf5 file per job on each node)
- Aggregation on one hdf5 file per job (after job termination)
- Slurm built-in tools for extraction of hdf5 profiling data

# Energy Accounting and Power Profiling Architecture



# acct_gather_energy Plugin - Overview

- One of a new family of **acct_gather** plugins that collect resource usage data for accounting, profiling and monitoring.
- Loaded by **slurmd** on each compute node.
- Called by **jobacct_gather** plugin to collect energy consumption accounting data for jobs and steps.
- Called separately via RPC from the **slurmctld background** thread to collect energy consumption data for nodes.
- Calls **acct_gather_profile** plugin to provide energy data samples for profiling.

# acct_gather_energy Plugin - Configuration

In **slurm.conf**

To configure plugin:

**AcctGatherEnergyType=acct_gather_energy/rapl** *or*
**AcctGatherEnergyType=acct_gather_energy/ipmi**

Frequency of node energy sampling controlled by:
**AcctGatherNodeFreq=<seconds>**
Default value is 0, which disables node energy sampling

Collection of energy accounting data for jobs/steps requires:
**JobAcctGatherType=jobacct_gather/linux** *or*
**JobAcctGatherType=jobacct_gather/cgroup**
Frequency of job accounting sampling controlled by:
**JobAcctGatherFrequency=task=<seconds>**
Default value is 30 seconds

In **acct_gather.conf** (new config file), for **acct_gather_energy/ipmi** only:

**EnergyIPMIFrequency**
**EnergyIPMICalcAdjustment**
**EnergyIPMIPowerSensor**
**EnergyIPMIUsername**
**EnergyIPMIPassword**

# acct_gather_energy Plugin – Data Reporting

- For running jobs, energy accounting data is reported by **sstat**.
- If accounting database is configured, energy accounting data is included in accounting records and reported by **sacct** and **sreport**.
- If **acct_gather_profile** plugin is configured, energy profiling data is reported by the method specified by the profile plugin type.
- Energy consumption data for nodes is reported by **scontrol show node**.
- Cumulative/total energy consumption is reported in units of **joules**.
- Instantaneous rate of energy consumption (power) is reported in units of **watts**.

# Out-of-band collection of power/energy data

- **External Sensors** Plugins to allow out-of-band monitoring of cluster sensors
- Possibility to Capture energy usage and temperature of various components (nodes, switches, rack-doors, etc)
- Framework generic but initial Support for RRD databases through rrdtool API (for the collection of energy/temperature data)
  - Plugin to be used with real wattmeters or out-of-band IPMI capturing
- Power data captured used for per node power monitoring (scontrol show node) and per job energy accounting (Slurm DB)
  - direct usage for energy reporting per job
  - but internal SLURM calculations for power reporting

# External Sensors Plugin - Purpose

**Plugin Name**: ext_sensors

**Purpose**: To collect environmental-type data from external sensors or sources for the following uses:

- Job/step accounting – Total energy consumption by a completed job or step (no energy data while job/step is running).
- Hardware monitoring – Instantaneous and cumulative energy consumption for nodes; instantaneous temperature of nodes.
- Future work will add additional types of environmental data, such as energy and temperature data for network switches, cooling system, etc. Environmental data may be used for resource management.

# ext_sensors Plugin - Overview

- Loaded by **slurmctld** on management node.
- Collects energy accounting data for jobs and steps independently of the **acct_gather** plugins.
  - Called by slurmctld request handler when step starts.
  - Called by slurmctld step manager when step completes.
- Since energy use by jobs/steps is measured only at completion (i.e., no sampling), does not support energy profiling or energy reporting for running jobs/steps (sstat).
- Called separately from the **slurmctld background** thread to sample energy consumption and temperature data for nodes.

# ext_sensors Plugin – Data Reporting

- If accounting database is configured, energy data is included in accounting records and reported by **sacct** and **sreport**.

- Energy consumption data for nodes is reported by **scontrol show node**.

- Cumulative/total energy consumption reported in **joules**.
- Instantaneous energy consumption rate (power) for nodes reported in **watts**.
- Node temperature reported in **celsius**.

# ext_sensors Plugin - Versions

- One version of **ExtSensorsType** plugin currently supported:
  - **ext_sensors/rrd**

    External sensors data is collected using RRD.  RRDtool is GNU-licensed software that creates and manages a linear database used for sampling or logging. The database is populated with energy data using out-of-band IPMI collection.

- Plugin API is described in Slurm developer documentation:
  - http://slurm.schedmd.com/ext_sensorsplugins.html

# ext_sensors Plugin - Configuration

- In **slurm.conf**

  To configure plugin:
  **ExtSensorsType=ext_sensors/rrd**

  Frequency of node energy sampling controlled by:
  **ExtSensorsFreq=<seconds>**
  Default value is 0, which disables node energy sampling

  Collection of energy accounting data for jobs/steps requires:
  **JobAcctGatherType=jobacct_gather/linux** *or* **cgroup**

- In **ext_sensors.conf** (new configuration file)

**JobData=energy** Specify the data types to be collected by the plugin for jobs/steps.
**NodeData=[energy|temp]** Specify the data types to be collected by the plugin for nodes.
**SwitchData=energy** Specify the data types to be collected by the plugin for switches.
**ColdDoorData=temp** Specify the data types to be collected by the plugin for cold doors.
**MinWatt=<number>** Minimum recorded power consumption, in watts.
**MaxWatt=<number>** Maximum recorded power consumption, in watts.
**MinTemp=<number>** Minimum recorded temperature, in celsius.
**MaxTemp=<number>** Maximum recorded temperature, in celsius.
**EnergyRRA=<name>** Energy RRA name.
**TempRRA=<name>** Temperature RRA name.
**EnergyPathRRD=<path>** Pathname of energy RRD file.
**TempPathRRD=<path>** Pathname of temperature RRD file.

# Example 1 – Node energy monitoring using acct_gather_energy/rapl

```
[sulu] (slurm) mnp> scontrol show config
...
AcctGatherEnergyType    = acct_gather_energy/rapl
AcctGatherNodeFreq      = 30 sec
...

[sulu] (slurm) mnp> scontrol show node n15
NodeName=n15 Arch=x86_64 CoresPerSocket=8
   CPUAlloc=0 CPUErr=0 CPUTot=32 CPULoad=0.00 Features=(null)
   Gres=(null)
   NodeAddr=drak.usrnd.lan NodeHostName=drak.usrnd.lan
   OS=Linux RealMemory=1 AllocMem=0 Sockets=4 Boards=1
   State=IDLE ThreadsPerCore=1 TmpDisk=0 Weight=1
   BootTime=2013-08-28T09:35:47 SlurmdStartTime=2013-09-05T14:31:21
   CurrentWatts=121 LowestJoules=69447 ConsumedJoules=8726863
   ExtSensorsJoules=n/s ExtSensorsWatts=0 ExtSensorsTemp=n/s
```

# Example 2 – Energy accounting using acct_gather_energy/rapl

```
[sulu] (slurm) mnp> scontrol show config
...
JobAcctGatherType       = jobacct_gather/linux
JobAcctGatherFrequency  = task=10
AcctGatherEnergyType    = acct_gather_energy/rapl
AccountingStorageType   = accounting_storage/slurmdb
...

[sulu] (slurm) mnp> srun test/memcputest 100 10000 &
[1] 20712
[sulu] (slurm) mnp> 100 Mb buffer allocated

[sulu] (slurm) mnp> squeue
             JOBID PARTITION     NAME     USER  ST       TIME  NODES NODELIST(REASON)
               120 drak-only memcpute    slurm   R       0:03      1 n15

[sulu] (slurm) mnp> sstat -j 120 -o ConsumedEnergy
ConsumedEnergy
--------------
          2149

[sulu] (slurm) mnp> sstat -j 120 -o ConsumedEnergy
ConsumedEnergy
--------------
          2452

[sulu] (slurm) mnp> sstat -j 120 -o ConsumedEnergy
ConsumedEnergy
--------------
          2720
[sulu] (slurm) mnp> Finished: j = 10001, c = 2990739969

[1]+  Done                    srun test/memcputest 100 10000

[sulu] (slurm) mnp> sacct -j 120 -o ConsumedEnergy
ConsumedEnergy
--------------
          3422
```

# Example 3 – Energy accounting using acct_gather_energy/ipmi

```
[root@cuzco108 bin]# scontrol show config
...
JobAcctGatherType       = jobacct_gather/linux
JobAcctGatherFrequency  = task=10
AcctGatherEnergyType    = acct_gather_energy/ipmi
AccountingStorageType   = accounting_storage/slurmdb
...

[root@cuzco108 bin]# cat /usr/local/slurm2.6/etc/acct_gather.conf

EnergyIPMIFrequency=10
#EnergyIPMICalcAdjustment=yes
EnergyIPMIPowerSensor=1280


[root@cuzco108 bin]# srun -w cuzco113 memcputest 100 10000 &
[1] 26138
[root@cuzco108 bin]# 100 Mb buffer allocated

[root@cuzco108 bin]# squeue
             JOBID PARTITION     NAME     USER ST       TIME  NODES NODELIST(REASON)
               101 exclusive memcpute     root  R       0:04      1 cuzco113
[root@cuzco108 bin]# sstat -j 101 -o ConsumedEnergy
ConsumedEnergy
--------------
           570

[root@cuzco108 bin]# sstat -j 101 -o ConsumedEnergy
ConsumedEnergy
--------------
         1.74K
```

# Example 3 – continued

```
[root@cuzco108 bin]# Finished: j = 10001, c = 2990739969

[1]+  Done                    srun -w cuzco113 memcputest 100 10000
[root@cuzco108 bin]# sacct -j 101 -o ConsumedEnergy
ConsumedEnergy
--------------
         1.74K
```

# Example 4 – Node energy and temperature monitoring using ext_sensors/rrd

```
[root@cuzco0 ~]# scontrol show config
...
ExtSensorsType          = ext_sensors/rrd
ExtSensorsFreq          = 10 sec
...

[root@cuzco108 slurm]# cat /usr/local/slurm2.6/etc/ext_sensors.conf
#
# External Sensors plugin configuration file
#

JobData=energy
NodeData=energy,temp

EnergyRRA=1
EnergyPathRRD=/BCM/data/metric/%n/Power_Consumption.rrd

TempRRA=1
TempPathRRD=/BCM/data/metric/%n/Temperature.rrd

MinWatt=4
MaxWatt=200


[root@cuzco0 ~]# scontrol show node cuzco109

NodeName=cuzco109 Arch=x86_64 CoresPerSocket=4
   CPUAlloc=0 CPUErr=0 CPUTot=8 CPULoad=0.00 Features=(null)
   Gres=(null)
   NodeAddr=cuzco109 NodeHostName=cuzco109
   OS=Linux RealMemory=24023 AllocMem=0 Sockets=2 Boards=1
   State=IDLE ThreadsPerCore=1 TmpDisk=0 Weight=1
   BootTime=2013-09-03T17:39:00 SlurmdStartTime=2013-09-10T22:58:10
   CurrentWatts=0 LowestJoules=0 ConsumedJoules=0
   ExtSensorsJoules=4200 ExtSensorsWatts=105 ExtSensorsTemp=66
```

# Example 5 – Energy accounting comparison using ext_sensors/rrd and acct_gather_energy/ipmi

The accuracy/consistency of energy measurements may be inaccurate if the run time of the job is short and allows for only a few samples. This effect should be reduced for longer jobs.

The following example shows that the **ext_sensors/rrd** and **acct_gather_energy/ipmi** plugins produce very similar energy consumption results for a MPI benchmark job using 4 nodes and 32 CPUs, with a run time of ~9 minutes.

# Example 5 – continued

**acct_gather_energy/ipmi**

```
[root@cuzco108 bin]# scontrol show config | grep acct_gather_energy
AcctGatherEnergyType    = acct_gather_energy/ipmi

[root@cuzco108 bin]# srun -n32 --resv-ports ./cg.D.32 &

[root@cuzco108 bin]# squeue
             JOBID PARTITION     NAME     USER ST       TIME  NODES NODELIST(REASON)
               122 exclusive  cg.D.32     root  R       0:02      4 cuzco[109,111-113]

[root@cuzco108 bin]# sacct -o "JobID%5,JobName,AllocCPUS,NNodes%3,NodeList%22,State,Start,End,Elapsed,ConsumedEnergy%9"
JobID    JobName  AllocCPUS NNo               NodeList      State               Start                 End    Elapsed ConsumedE
----- ---------- ---------- --- ---------------------- ---------- ------------------- ------------------- ---------- ---------
  127    cg.D.32         32   4     cuzco[109,111-113]  COMPLETED 2013-09-12T23:12:51 2013-09-12T23:22:03   00:09:12   490.60K
```

**ext_sensors/rrd**

```
[root@cuzco108 bin]# scontrol show config | grep ext_sensors
ExtSensorsType          = ext_sensors/rrd

[root@cuzco108 bin]# srun -n32 --resv-ports ./cg.D.32 &

[root@cuzco108 bin]# squeue
             JOBID PARTITION     NAME     USER ST       TIME  NODES NODELIST(REASON)
               128 exclusive  cg.D.32     root  R       0:02      4 cuzco[109,111-113]

[root@cuzco108 bin]# sacct -o "JobID%5,JobName,AllocCPUS,NNodes%3,NodeList%22,State,Start,End,Elapsed,ConsumedEnergy%9"
JobID    JobName  AllocCPUS NNo               NodeList      State               Start                 End    Elapsed ConsumedE
----- ---------- ---------- --- ---------------------- ---------- ------------------- ------------------- ---------- ---------
  128    cg.D.32         32   4     cuzco[109,111-113]  COMPLETED 2013-09-12T23:27:17 2013-09-12T23:36:33   00:09:16   498.67K
```

# Job Execution Profiling

# What is Profiling in Slurm?

Detailed collection of performance data of a parallel job

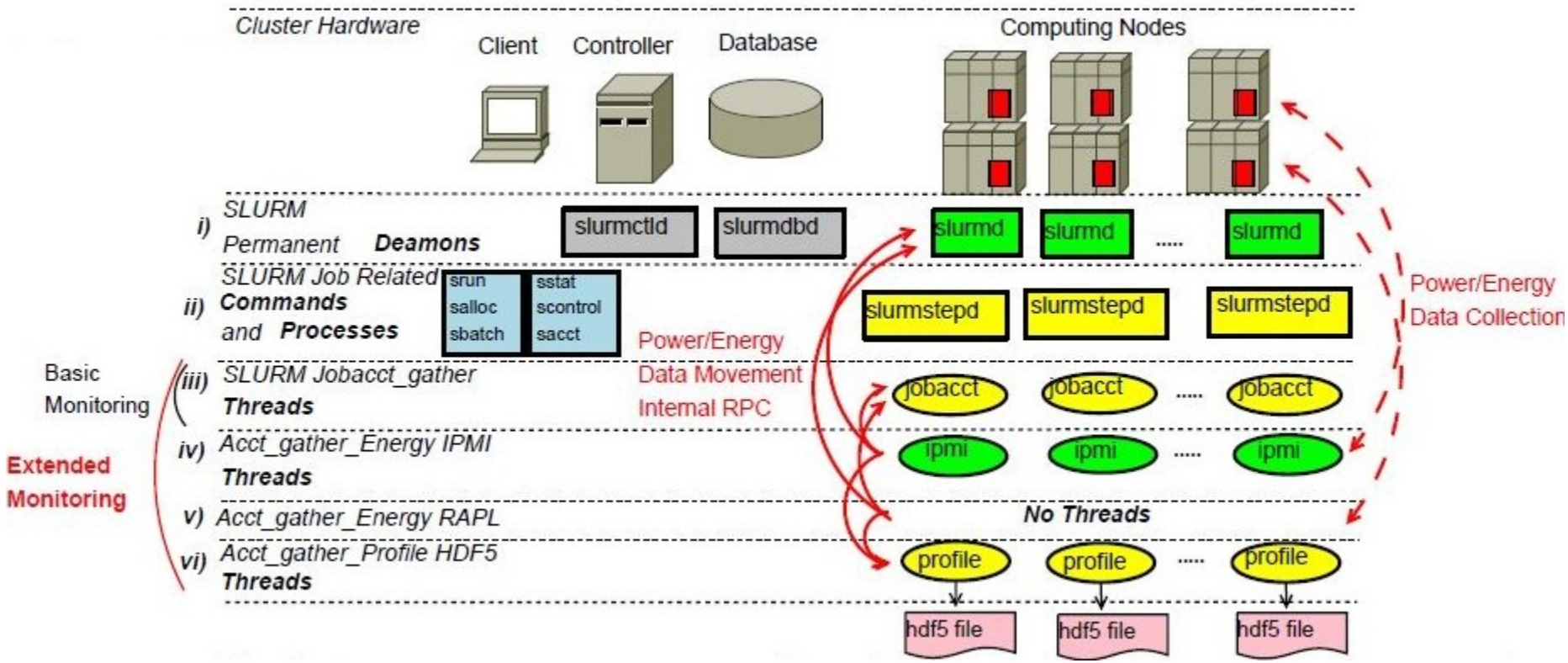
- More detail than can reasonably be stored in an accounting database
- Data from all tasks on all nodes consolidated in one (HDF5) dataset
- Controls to limit data collection to only a few jobs to minimize overhead on the entire system

- Profiling with HDF5:
  - introduced in SLURM 2.6 version
  - extended and improved in SLURM 15.08 version

# Why Profile?

- Profiling has traditionally been used to improve an applications use of resources, particularly CPUs
- There is an increasing need to improve the scheduling and placement of an application on the resources of the supercomputer
- It is now important to schedule applications to efficiently use energy and air conditioning
- It is also important to allocate resources that are physically close together to minimize network latency for both message passing and use of parallel file systems

# Profile Plugin Architecture




After the job terminates, sh5util is used to merge the node step HDF5 files into a job HDF5 file

# Data Flow

- While a job executes, the data collection plugins are periodically called on each node (by Slurmstepd)
- They in turn call the framework plugin to add_sample
- The Profile plugin stores the data in a ***node-step*** HDF5 file on a shared file system
- When the job ends, sh5util merges all the node-step files into one ***job*** HDF5 file (This isn't automatic but is often done as an additional sbatch in an sbatch script)
- sh5util can also extract subsets of data as a text file to be imported into other analysis tools such as spreadsheets

The HDF Group

www.hdfgroup.org

# What is HDF5?

- A system widely used in HPC supporting structured data.
- **Has a versatile data model** that can represent very complex data objects and a wide variety of metadata
- **Has a completely portable file format** with no limit on the number or size of data objects stored
- **Has an open source software library** that runs on a wide range of computational platforms, from cell phones to massively parallel systems, and implements a high-level API with C, C++, Fortran 90, and Java interfaces
- **A rich set of integrated performance features** that allow access time and storage space optimizations
- **Tools and applications** for managing, manipulating, viewing, and analyzing the data in the collection

# HDF5 File Structure

- The internal structure of a HDF5 file resembles a file system with **groups** being similar to *directories* and **data sets** being similar to *files*
- A data set is a multi-dimensional array of elements with supporting metadata
- **Attributes** can be attached to groups to store application defined properties

# Profiler Use of HDF5 Structure

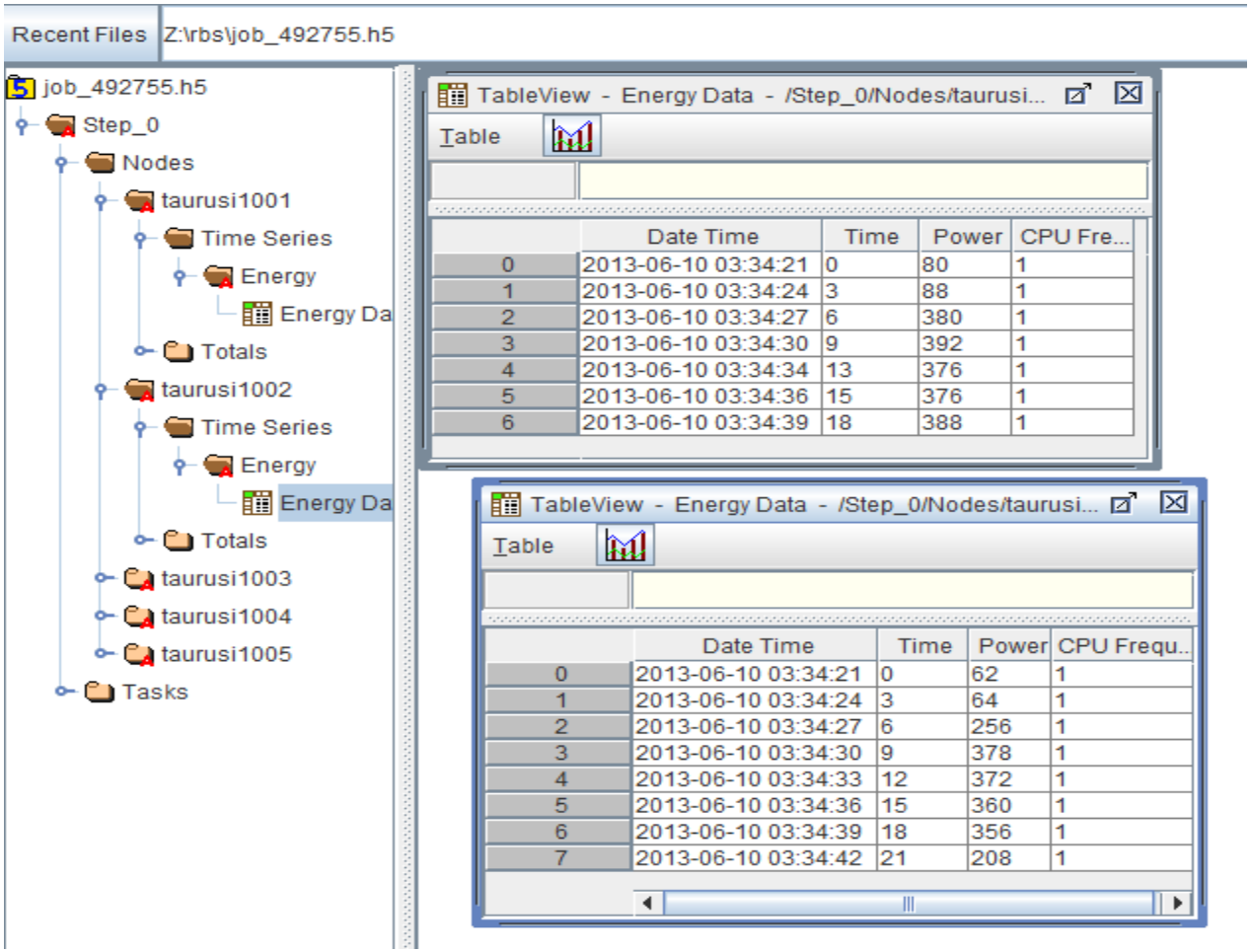
- In the **job** file, there will be a *group* for each **step** of the job
- Within each step, there will be a *group* for **Nodes**, and a *group* for **Tasks**
  - The **Nodes** group will have a *group* for each **node** in the step allocation
    - For each node group, there is a *group* for **Time Series** and another for **Totals**
      - The *Time Series* group contains a *group/dataset* containing the time series for each data type collected
      - The *Totals* group contains a corresponding *group/dataset* that has the Minimum, Average, Maximum, and Sum Total for each item in the time series
  - The **Tasks** group will only contain a *group* for each task. It primarily contains an attribute stating the node on which the task was executed. This set of groups is essentially a cross reference table.

# HDFView

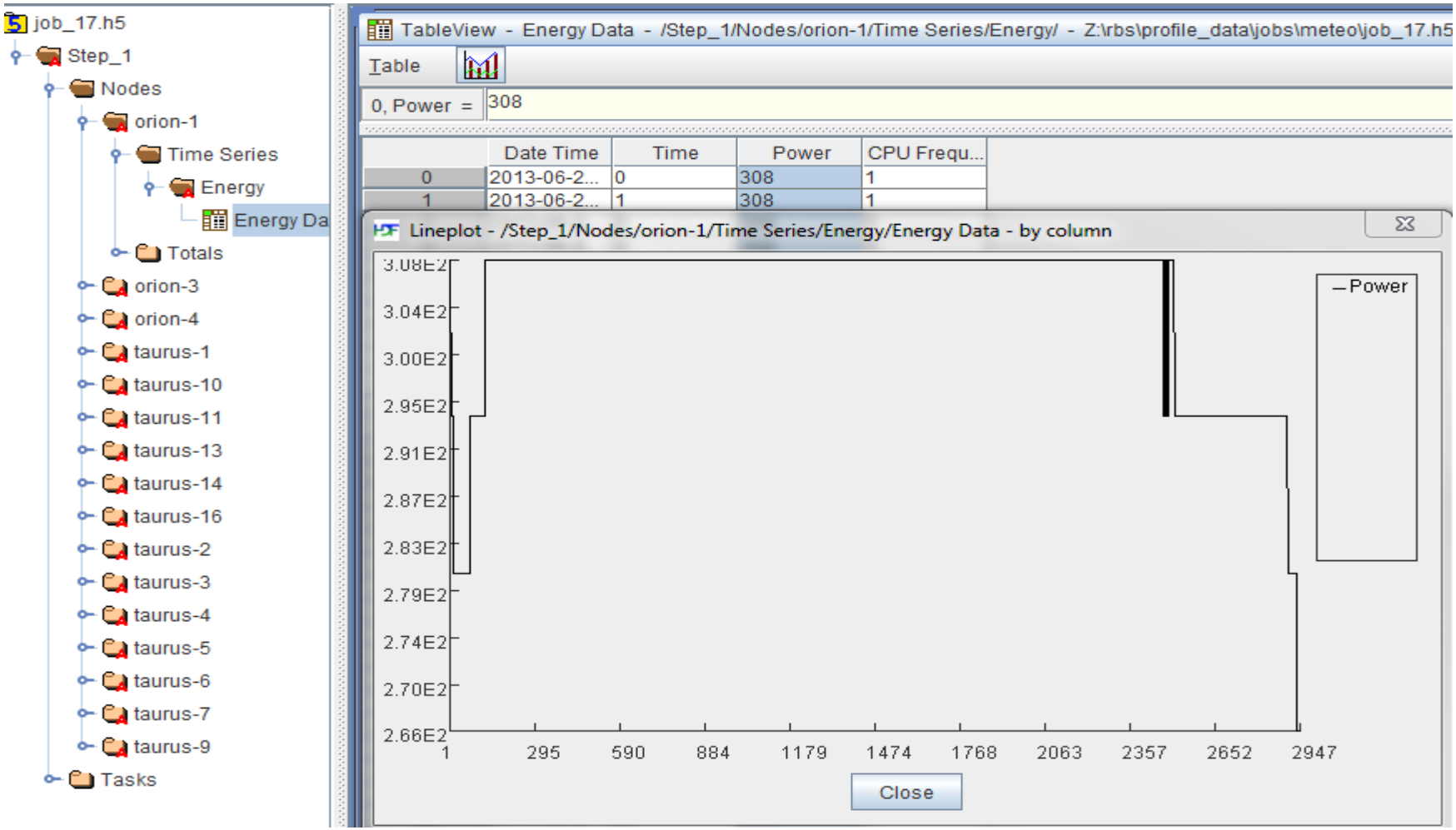
- **HDFView** is a visual tool for browsing and editing HDF4 and HDF5 files. Using HDFView, you can view a file hierarchy in a tree structure.

- http://www.hdfgroup.org/hdf-java-html/hdfview/

# HDFView example



# HDFView Graph



# Profiling Jobs …

- **Data Consolidation**

  The node-step files are merged into one HDF5 file for the job using the **sh5util** program. They are then deleted.

  e.g. sbatch -n1 -d$Slurm_JOB_ID --wrap="sh5util -j $Slurm_JOB_ID"

- **Data Extraction**

  The **sh5util** program can also extract all samples for a specific data item from a time series and write a comma separated value (csv) file for importation into other analysis tools such as spreadsheets.

  e.g. sh5util -j 42 –item-extract --series=Energy --data=power

# csv Output in Spreadsheet

| TOD | Et | JobId | StepId | Min Node | Min power | Ave power | Max Node | Max power | Total power | Num Nodes | taurusi1001 | taurusi1002 | taurusi1003 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 6/10/2013 3:34 | 0 | 492755 | 0 | taurusi1002 | 62 | 69.6 | taurusi1001 | 80 | 348 | 5 | 80 | 62 | 68 |
| 6/10/2013 3:34 | 3 | 492755 | 0 | taurusi1002 | 64 | 77.6 | taurusi1005 | 100 | 388 | 5 | 88 | 64 | 72 |
| 6/10/2013 3:34 | 6 | 492755 | 0 | taurusi1002 | 256 | 326 | taurusi1005 | 390 | 1630 | 5 | 380 | 256 | 334 |
| 6/10/2013 3:34 | 9 | 492755 | 0 | taurusi1002 | 378 | 388 | taurusi1003 | 394 | 1940 | 5 | 392 | 378 | 394 |
| 6/10/2013 3:34 | 12 | 492755 | 0 | taurusi1002 | 372 | 381.2 | taurusi1005 | 400 | 1906 | 5 | 376 | 372 | 382 |
| 6/10/2013 3:34 | 15 | 492755 | 0 | taurusi1002 | 360 | 370 | taurusi1003 | 384 | 1850 | 5 | 376 | 360 | 384 |
| 6/10/2013 3:34 | 18 | 492755 | 0 | taurusi1004 | 352 | 368.8 | taurusi1005 | 392 | 1844 | 5 | 388 | 356 | 356 |
| 6/10/2013 3:34 | 21 | 492755 | 0 | taurusi1002 | 208 | 233 | taurusi1005 | 280 | 932 | 4 | 0 | 208 | 216 |

# Profiling framework improvements in 15.08 version

▶SLURM application profiling HDF5 framework improved internals for scalability purposes:

| NEMO upon 8 nodes (~13min) | Per node hdf5 file size | Time for merge | Merged hdf5 file size |
|---|---|---|---|
| Slurm-14.11 | 5.9 MB | 1.985 sec | 3.8 MB |
| Slurm-15.08 | 320 KB | 0.059 sec | 2.5 MB |

- New more scalable and flexible architecture
  - AcctGatherProfile operates as a service
- Based upon the high level HDF5 API
  - Added features such as data compression
- Update sh5util (kept backward compatibility)
  - Calculate statistics during merge and not during processing



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# Profiling Configuration

- Configuration parameters

  The profile plugin is enabled in the **slurm.conf** file, but is internally configured in the **acct_gather.conf** file.

## slurm.conf parameters

- **AcctGatherProfileType**=acct_gather_profile/hdf5 enables the HDF5 Profile Plugin
- **JobAcctGatherFrequency**={energy=freq {,lustre=freq {,network=freq , {task=freq}}}} sets default sample frequencies for data types.
- One or more of the following plugins must also be configured.
  - AcctGatherEnergyType=acct_gather_energy/ipmi
  - AcctGatherEnergyType=acct_gather_energy/rapl
  - AcctGatherFilesystemType=acct_gather_filesystem/lustre
  - AcctGatherInfinibandType=acct_gather_infiniband/ofed
  - JobAcctGatherType=job_acct_gather/linux

# Sample conf files

## slurm.conf

```
DebugFlags=Profile
AcctGatherProfileType=acct_gather_profile/hdf5

JobAcctGatherType=jobacct_gather/linux
JobAcctGatherFrequency=energy=5,lustre=60,network=60,task=60
AcctGatherEnergyType=acct_gather_energy/ipmi
AcctGatherFilesystemType=acct_gather_filesystem/lustre
AcctGatherInfinibandType=acct_gather_infiniband/ofed
```

## acct_gather.conf

```
# Parameters for AcctGatherEnergy/ipmi plugin
EnergyIPMIFrequency=10
EnergyIPMICalcAdjustment=yes
#
# Parameters for AcctGatherProfileType/hdf5 plugin
ProfileHDF5Dir=/app/Slurm/profile_data
# Parameters for AcctGatherInfiniband/ofed plugin
InfinibandOFEDFrequency=4
InfinibandOFEDPort=1
```

# Energy Data

- AcctGatherEnergyType=acct_gather_energy/ipmi is required in slurm.conf to collect energy data.
- JobAcctGatherFrequeny=Energy=<freq> should be set  in either slurm.conf  or via –acctg-freq command line option.

The IPMI energy plugin also needs the EnergyIPMIFrequency value set in the acct_gather.conf file. This sets the rate at which the plugin samples the external sensors. This value should be the same as the energy=sec in either JobAcctGatherFrequency or --acctg-freq.

Note that the IPMI and profile sampling is not synchronous. The profile sample simply takes the last available IPMI sample value. If the profile energy sample is more frequent than the IPMI sample rate, the IPMI value will be repeated. If the profile energy sample is greater than the IPMI rate, IPMI values will be lost.

Also note that smallest effective IPMI (EnergyIPMIFrequency) sample rate for 2013 era Intel processors is 3 seconds.

Note that Energy data is collected for the entire node so it is only meaningful for exclusive allocations.

- Each data sample in the Energy Time Series contains the following data items.

**Date Time** Time of day at which the data sample was taken.
This can be used to correlate activity with other sources such as logs.
**Time** Elapsed time since the beginning of the step.
**Power** Power consumption during the interval.
**CPU Frequency** CPU Frequency at time of sample in kilohertz.

# Lustre Data

- AcctGatherFilesystemType=acct_gather_filesystem/lustre is required in Slurm.conf to collect lustre data.
- JobAcctGatherFrequeny=Lustre=<freq> should be set  in either Slurm.conf or via –acctg-freq command line option.

- Each data sample in the Lustre Time Series contains the following data items.

| | |
|---|---|
| **Date Time** | Time of day at which the data sample was taken. This can be used to correlate activity with other sources such as logs. |
| **Time** | Elapsed time since the beginning of the step. |
| **Reads** | Number of read operations. |
| **MegabytesRead** | Number of megabytes read. |
| **Writes** | Number of write operations. |
| **MegabytesWrite** | Number of megabytes written. |

# Network (Infiniband) Data

- AcctGathertInfinibandType=acct_gather_infiniband/ofed is required in Slurm.conf to collect Network data.
- JobAcctGatherFrequeny=Network=<freq> should be set in either Slurm.conf or via –acctg-freq command line option.

- Each data sample in the Network Time Series contains the following data items.

| | |
|---|---|
| **Date Time** | Time of day at which the data sample was taken. This can be used to correlate activity with other sources such as logs. |
| **Time** | Elapsed time since the beginning of the step. |
| **PacketsIn** | Number of packets coming in. |
| **MegabytesIn** | Number of megabytes coming in through the interface. |
| **PacketsOut** | Number of packets going out. |
| **MegabytesOut** | Number of megabytes going out through the interface. |

# Task Data

- JobAcctGatherType=jobacct_gather/linux is required in Slurm.conf to collect task data
- JobAcctGatherFrequeny=Task=<freq> should be set in either Slurm.conf or via –acctg-freq command line option.

  The frequency should be set to at least 30 seconds for CPU utilization to be meaningful (since the resolution of cpu time in linux is 1 second)

- Each data sample in the Task Time Series contains the following data items.

**Date Time** Time of day at which the data sample was taken.
This can be used to correlate activity with other sources such as logs.
**Time** Elapsed time since the beginning of the step.
**CPUFrequency** CPU Frequency at time of sample.
**CPUTime** Seconds of CPU time used during the sample.
**CPUUtilization** CPU Utilization during the interval.
**RSS** Value of RSS at time of sample.
**VMSize** Value of VM Size at time of sample.
**Pages** Pages used in sample.
**ReadMegabytes** Number of megabytes read from local disk.
**WriteMegabytes** Number of megabytes written to local disk.

# Emulation and Performance Evaluation

# Activating emulation technique within SLURM

Multiple slurmd technique can be used to experiment with larger scales:

- the idea is that multiple slurmd deamons use the same IP address but different ports
- all controller side plugins and mechanisms will function
- ideal for scheduling, internal communications and scalability experiments

1. You need to run ./configure with –enable-multiple-slurmd parameter (make, make install, etc)
2. Perform the necessary changes in the slurm.conf file similarly the following example:

# Activating emulation technique within SLURM

```
SlurmdPidFile=/usr/local/slurm-test/var/run/slurmd-%n.pid
SlurmdSpoolDir=/tmp/slurm-%n
SlurmdLogFile=/tmp/slurmd-%n.log
FastSchedule=2
PartitionName=exclusive Nodes=virtual[0-40] Default=YES MaxTime=INFINITE State=UP Priority=10
Shared=EXCLUSIVE
NodeName=DEFAULT Sockets=2 CoresPerSocket=8 ThreadsPerCore=1 RealMemory=21384 State=IDLE
NodeName=virtual0 NodeHostName=nazgul NodeAddr=127.0.0.1 Port=17000
NodeName=virtual1 NodeHostName=nazgul NodeAddr=127.0.0.1 Port=17001
NodeName=virtual2 NodeHostName=nazgul NodeAddr=127.0.0.1 Port=17002
.....
```

3. You can start the slurmd deamons with:
   - Either through a script such as:

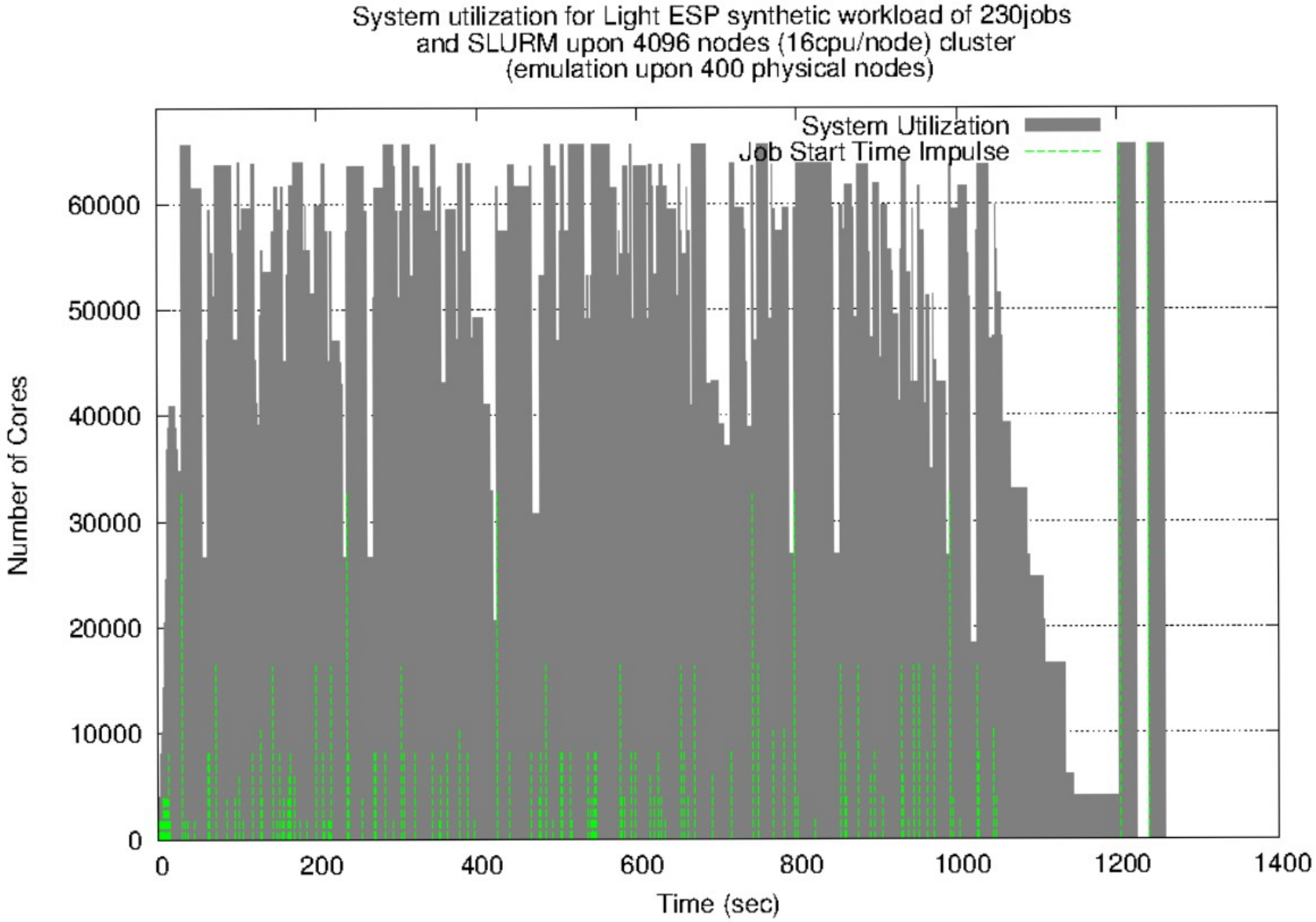
     for i in {0..40}; do slurmd -N virtual$i; done

   - Or by exporting: MULTIPLE_SLURMD="$(grep NodeHostName=$(hostname) /etc/slurm.conf | cut -d ' ' -f 1 | cut -d'=' -f 2)"

     on /etc/sysconfig/slurm and starting with /etc/init.d/slurm

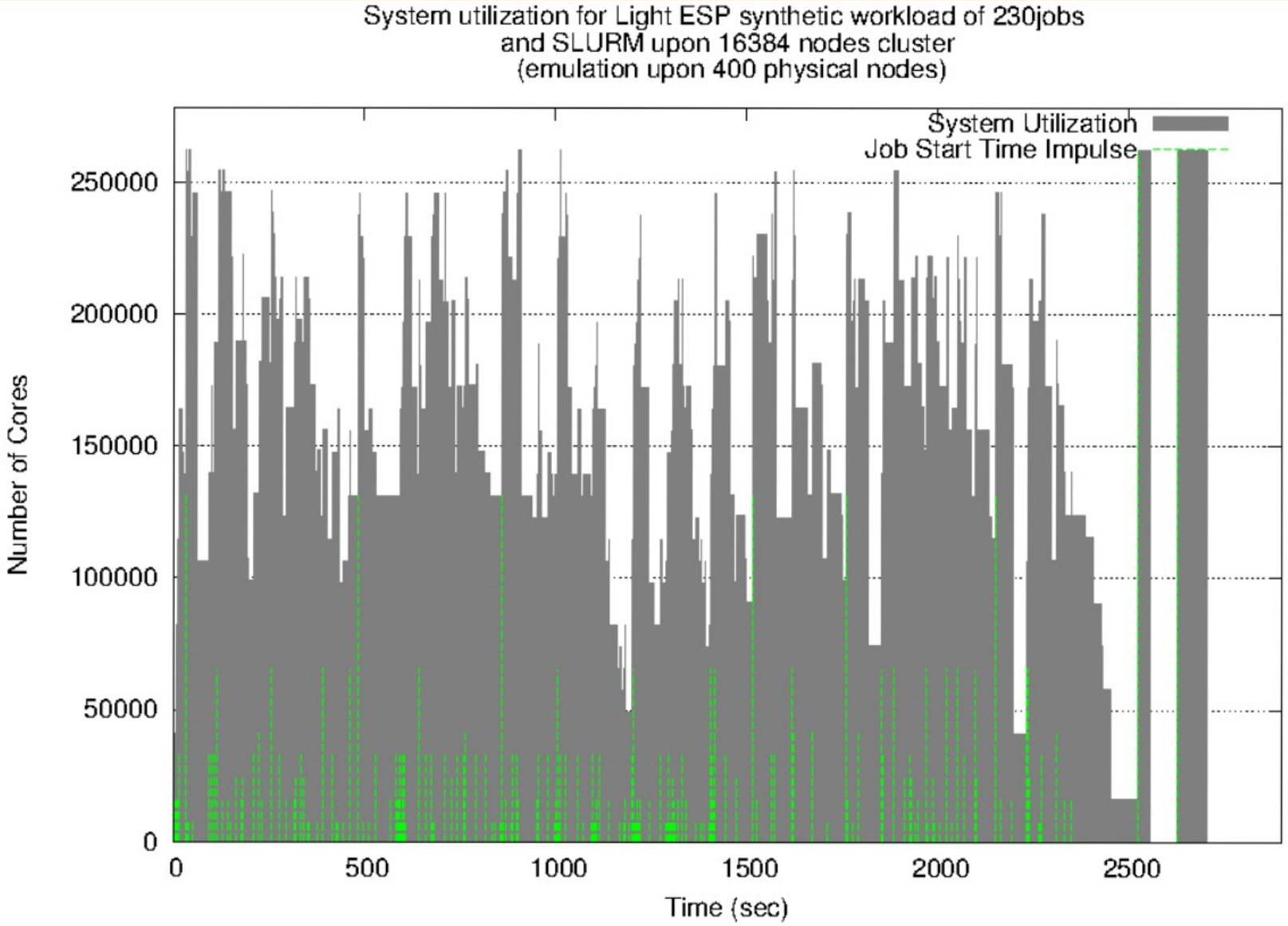
# Examples of performance evaluation with emulation

## 4096 emulated nodes upon 400 physical nodes



# Examples of performance evaluation with emulation

## 16384 emulated nodes upon 400 physical nodes

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