# CKRM:

# Class-based Prioritized Resource Control in Linux

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# Outline

- Motivation
- Framework
- Classification
- CPU
- Memory
- I/O
- Network
- Conclusions

# Linux Kernel Resource Management

- Process centric
  - `nice` value for cpu
  - `rss` limits for memory
  - Flexible outbound network QoS
- Performance isolation mechanisms are weak
- New "fairshare" proposals still process/user centric
    - fairshare cpu scheduler (RvR)
    - Complete Fair Queueing I/O (Jens Axboe/AA)

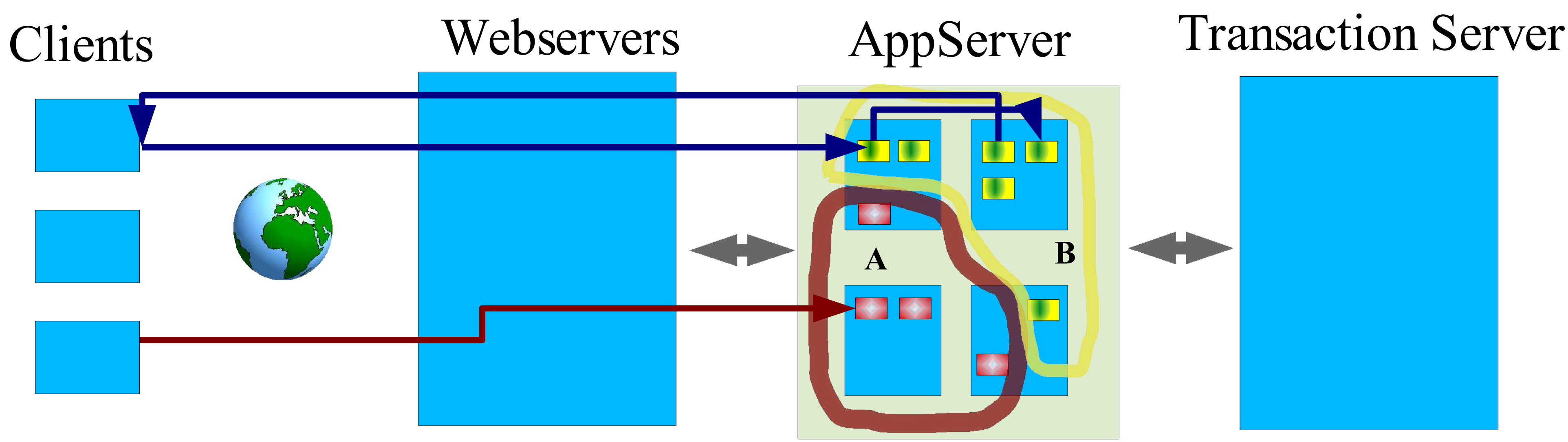
# Server Requirements

- “Work” (users, transaction, appl, ..) has varying levels of importance unknown to the kernel
- Different “work” is colocated in a single system
- Need ability to classify work by importance
- Need ability to differentiate service provided
  - QoS is typically based on end-user goals
    - Transaction latency, bandwidth, response time
  - Resource share needs to be specified external to kernel
- Monitor resource consumption by “work”

# What is Class-based Kernel Resource Management ?

- Attempt to make Linux kernel meet said server requirements better
- Driving Principles for CKRM
  - Flexible, dynamic grouping of processes into classes
  - Resource shares for each class
  - Kernel enforcement of shares for each phys resource
    - Requires scheduler (cpu,mem,i/o,net) modifications
  - Grouping rules and shares specified externally through a system wide policy

# Target Scenario 1: Enterprise Server Configuration

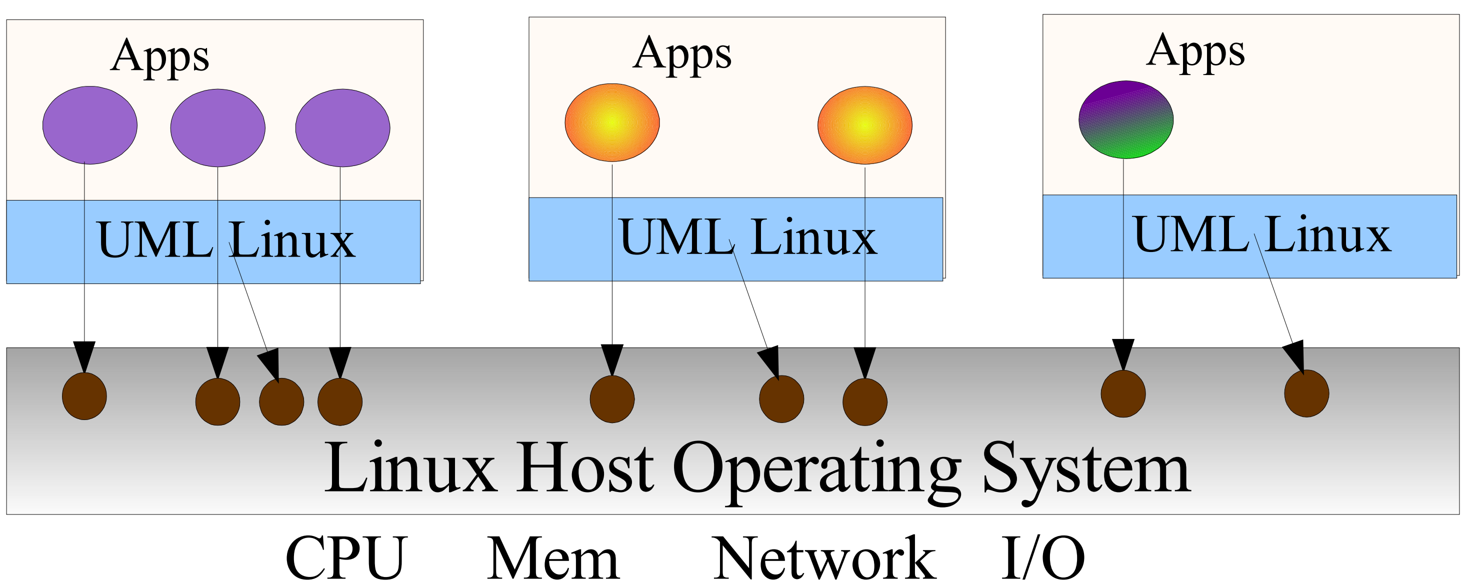



- Class determined by
  - who, how, what
- Different expected QoS for each class:
  - Response time, bandwidth utilization

- Example Stock trading:
  - **Gold**: high volume trader initiating a transaction
  - **Silver**: all other stock trading
  - **Bronze**: mutual fund transactions quotes

# Target Scenario 2: Virtual Hosting

- Virtual Hosting using UML, apps run as processes under host system together with guest OS
- Every system  resource needs to be regulated
- Service guarantees for each UML instance



# Target Scenario 3: Desktop

- More control over performance isolation of activities:
  - Compile code while (emailing , listening to music ..)
  - Scheduled Backup disk / Virus check while working
  - Limitations for ftp / telnet sessions

# Why kernel changes ?

- From user space certain QoS can not be done
  - Some limits do not exist ( e.g. I/O bandwidth )
  - Some hard to specify for dynamic workloads
- Kernel is central agent for resource control
  - Natural place to do “this kind of stuff”
  - Thesis: this can be done with modest changes to code and performance of existing resource schedulers

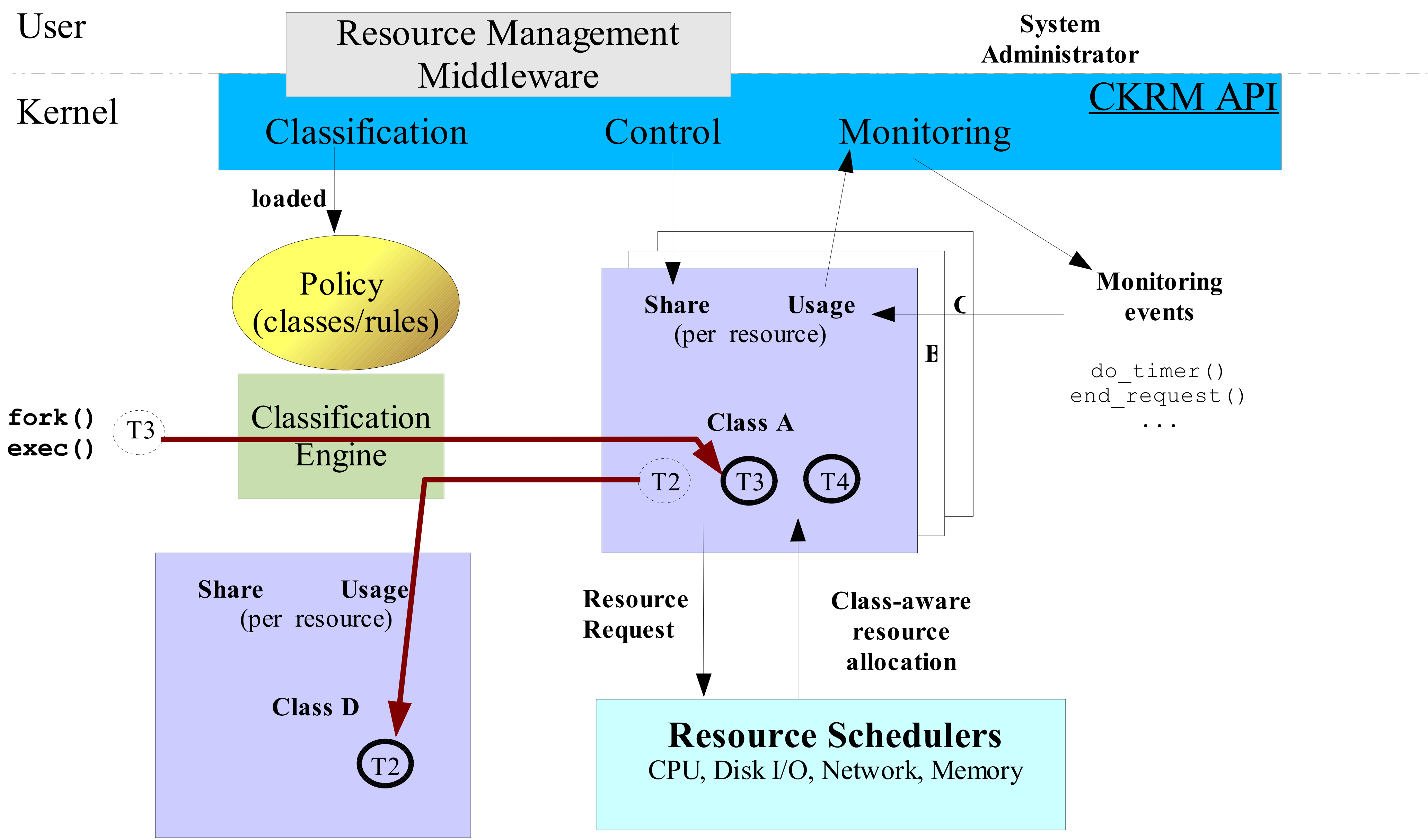
# CKRM : Key Concepts

- Class
  - Policy-defined grouping of tasks/mm's doing work at a common importance level e.g.
    - All web requests from customer X
    - All work initiated by user Y
  - Tasks can dynamically change classes
- Share
  - Portion of a resource that a class can use
  - Dynamically specified by entity external to OS
    - Direct specification by sys-admin/user
    - Indirectly through a root-level userland control program

# Classification

- Classification rule
  - { [ (attr,value) ]+ -> class }
  - Attrs of task: uid, gid, executable, application tag
- Policy
  - classes + classification rules
- Application tags
  - Additional flexibility for grouping based on application specific criteria
- Classification takes place
  - fork(), exec(), setuid(), setgid(), explicit call

# CKRM Framework



# Physical resources controlled

- CPU: timer ticks
- Memory: #physical pages used
- I/O: #bytes transferred per disk
  - Separate share for each disk visible to OS
- Inbound network: #connections accepted

# Monitoring

- Assess utilization
  - Capacity planning
- Accurate billing
  - Benefit independent of ability to regulate usage
- Feedback for control settings
- Operates at different time scales
  - Cumulative since policy load
  - Since last invocation of "get data"
- Currently no monitoring API exposed

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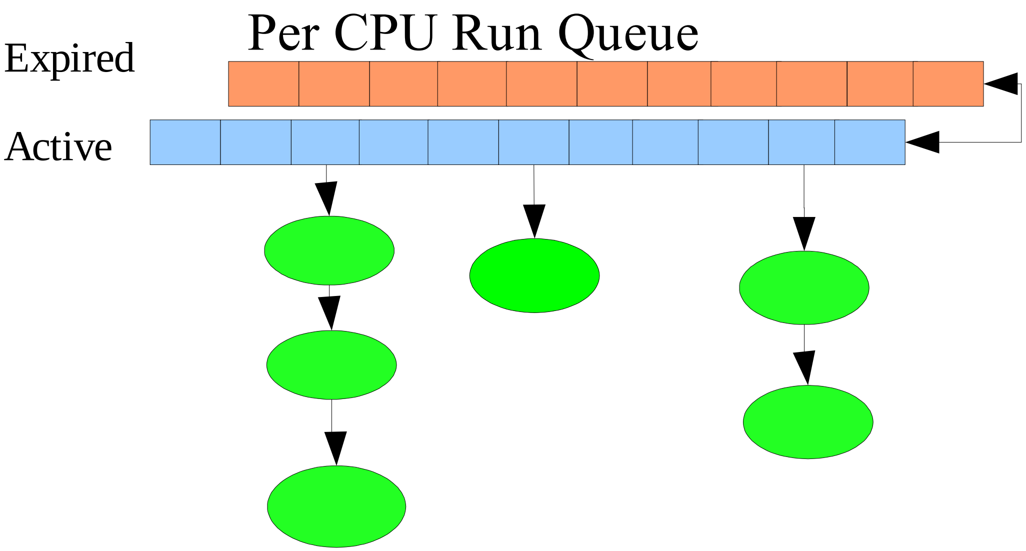
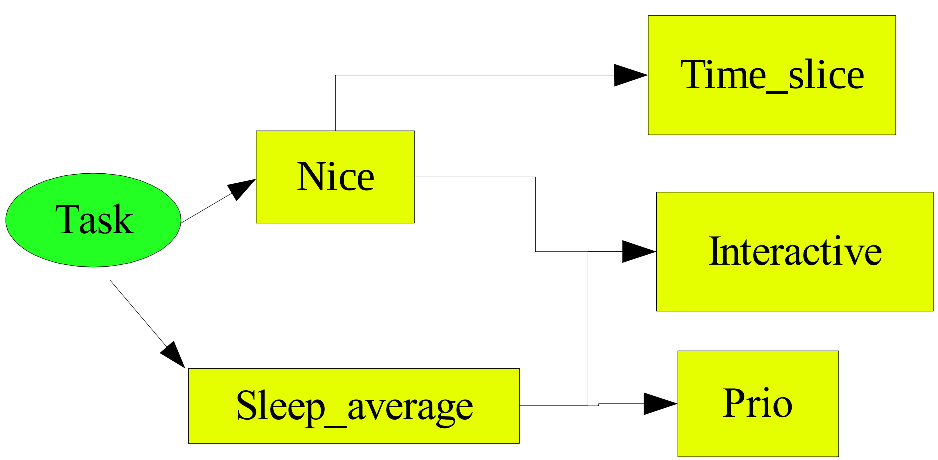
# Linux 2.5 Scheduler

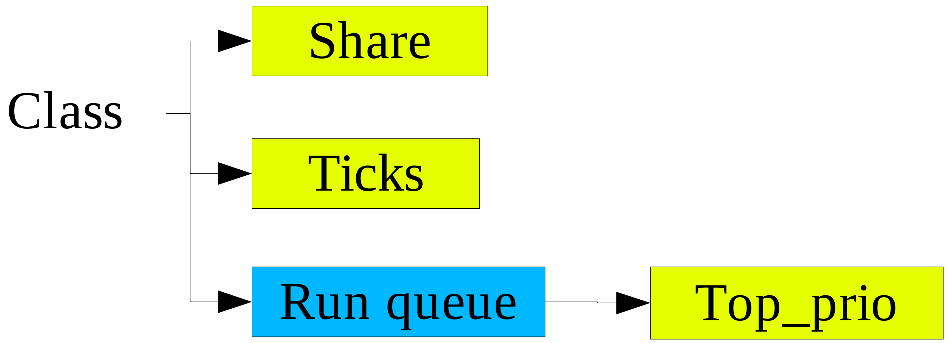



- Ordered by process priority
- Operations (enqueue, dequeue, get_next_task) are O(1)
- Priority and interactiveness are determined by nice value and sleep_average
- time_slice is determined by nice value, task will expired after time_slice ticks consumed
- Interactive jobs will not expire if they don't starve other processes
- Switch active and expired queue when all tasks expired

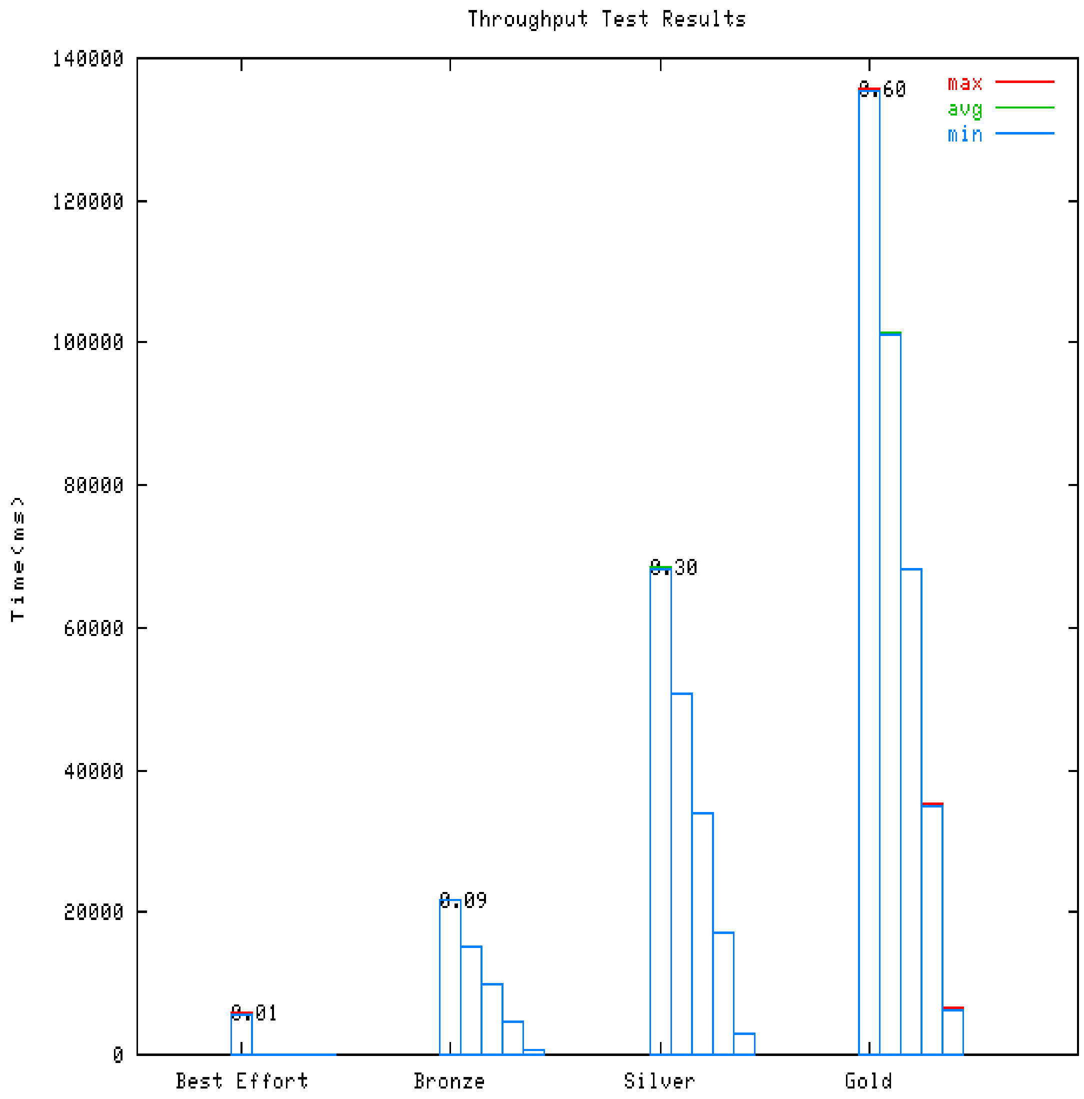
# Class Fair Share Scheduler

- Each class has its own runqueue
- Minimal changes to the existing scheduler:
  - same runqueue structure
  - same way to calculate time_slice, sleep_average and prio, etc.
  - same O(1) behavior within class
- **`get_next_task()`** now makes **2** decision
  - First selects the next class to run
  - Then, within that class select the top priority task just as today




- **Class Selection**:
  - Based on accumulative normalized time per class
    - **ecp(C) = Σ ticks(C)/share(C)**
    - monotonic increasing function
  - Select class C with **min(ecp(C))**
  - Consider finite sliding window CWIN [min..min+WS]
  - min=min(ecp(C)); WS ~ 128,256
  - When a class is reactivated (task is rescheduled)
    - **`if`** (min <= ecp(C) < min+WS)
      **`then`** insert C at WIN[ecp(C)]
      **`else`** insert C at WIN[min].
  - Provides fairness (shares) only
- **Urgency** (Interactivity)
  - **ecp(C) = (Σticks(C)/share(C)) * scale + top_prio**
  - High priority in class gives a short term boost
- **Scheduler maintains O(1) characteristics**

# Throughput Measurement

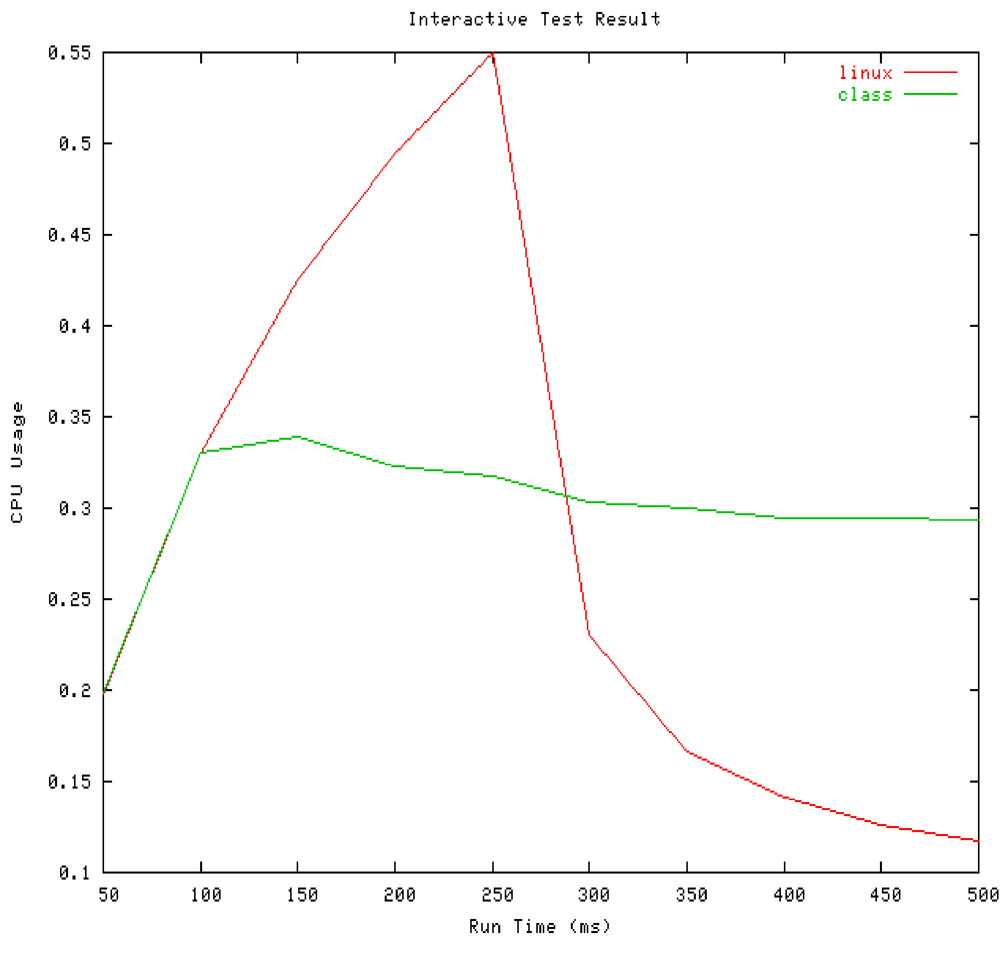


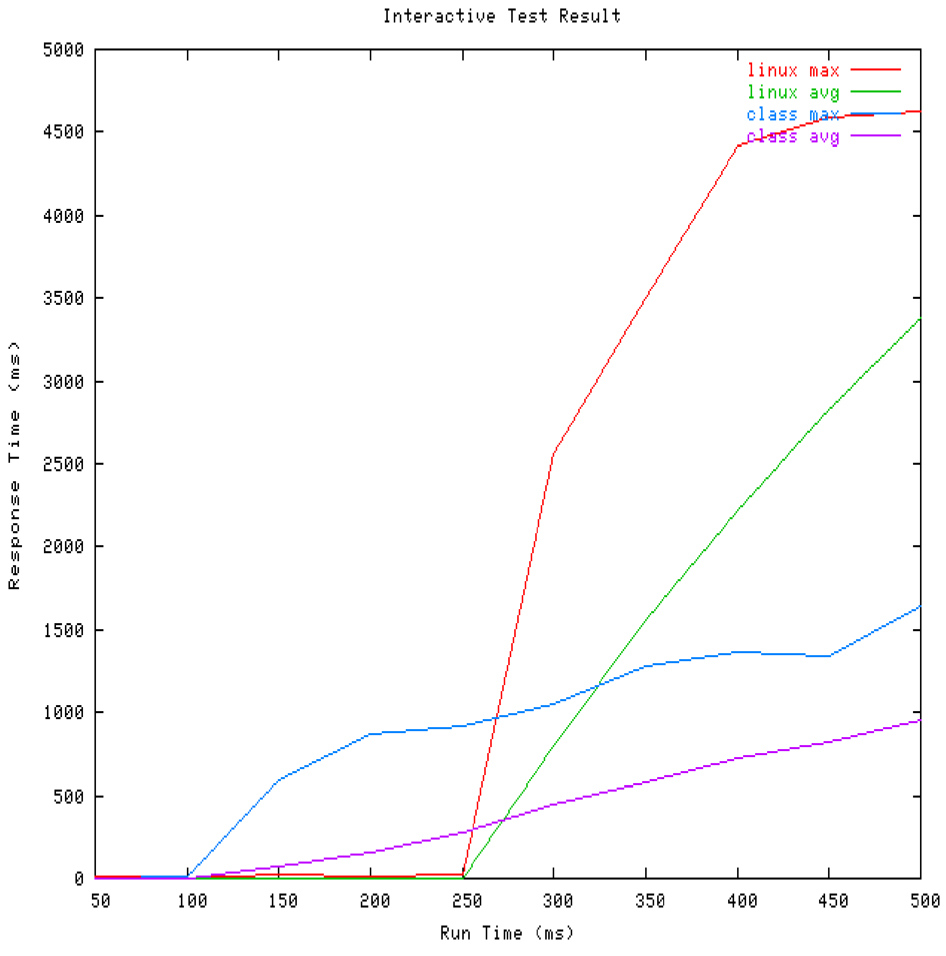

- 4 classes, with share of (60,30,9,1) respectively
- Each class has 5*3=15 cpu bound jobs with nice value of (-20, -10, 0, 10, 19) respectively
- Fair Sharing among classes: The CPU time received by the classes are propotional to its share (60:30:9:1) during the 30 minutes run.
- Fair to processes within a class: CPU time is propotional to its time_slice (200:151:102:54:10)
- Behavior exactly as desired
  - Same as O(1) within a class
  - Observing shares

# Interactiveness Measurement

- Exprimental Setting
  - 4 classes, with share of (60,30,9,1) respectively
  - Run cpu bound jobs on gold,blonze and best effort class
  - Run *one* interactive job in silver class (30%).
    - The interactive job will run for N ms;
    - then sleep for 200ms.
    - N varies from 50 to 500ms.

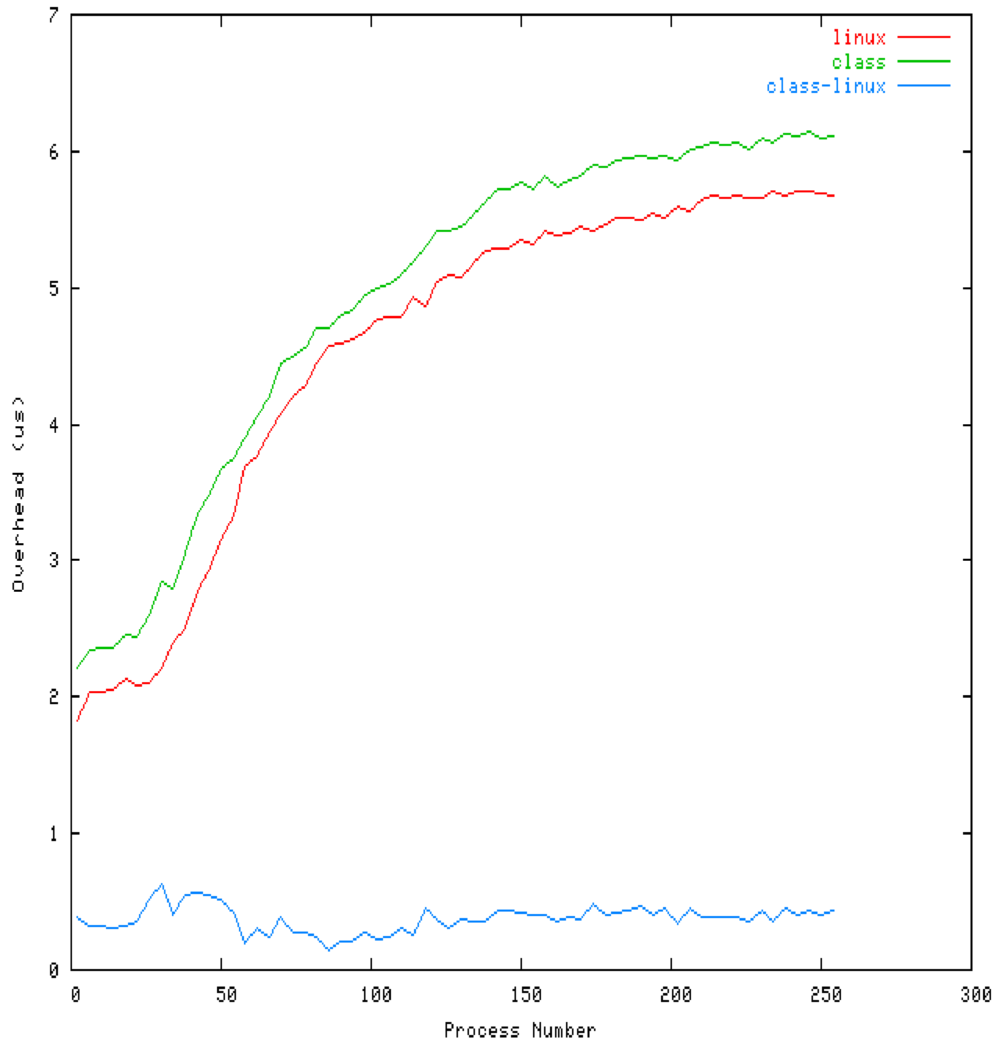
# Interactiveness Measurement (cont.)




Using CFS the cpu usage of the interactive job is roughly 30%
Class Fair Scheduler receive much smooth service because of performance isolation

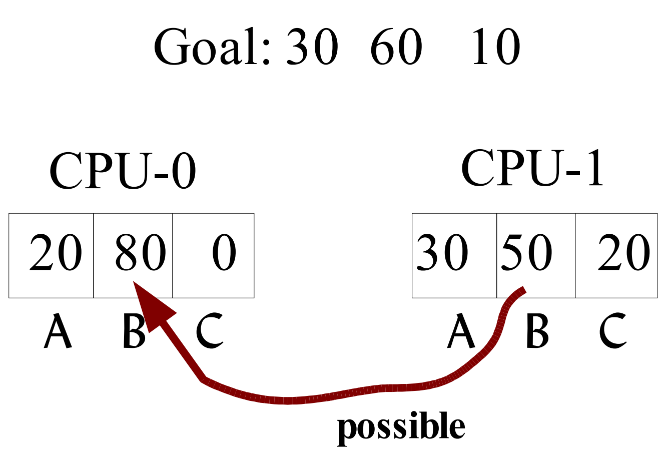
# Scheduling Overhead



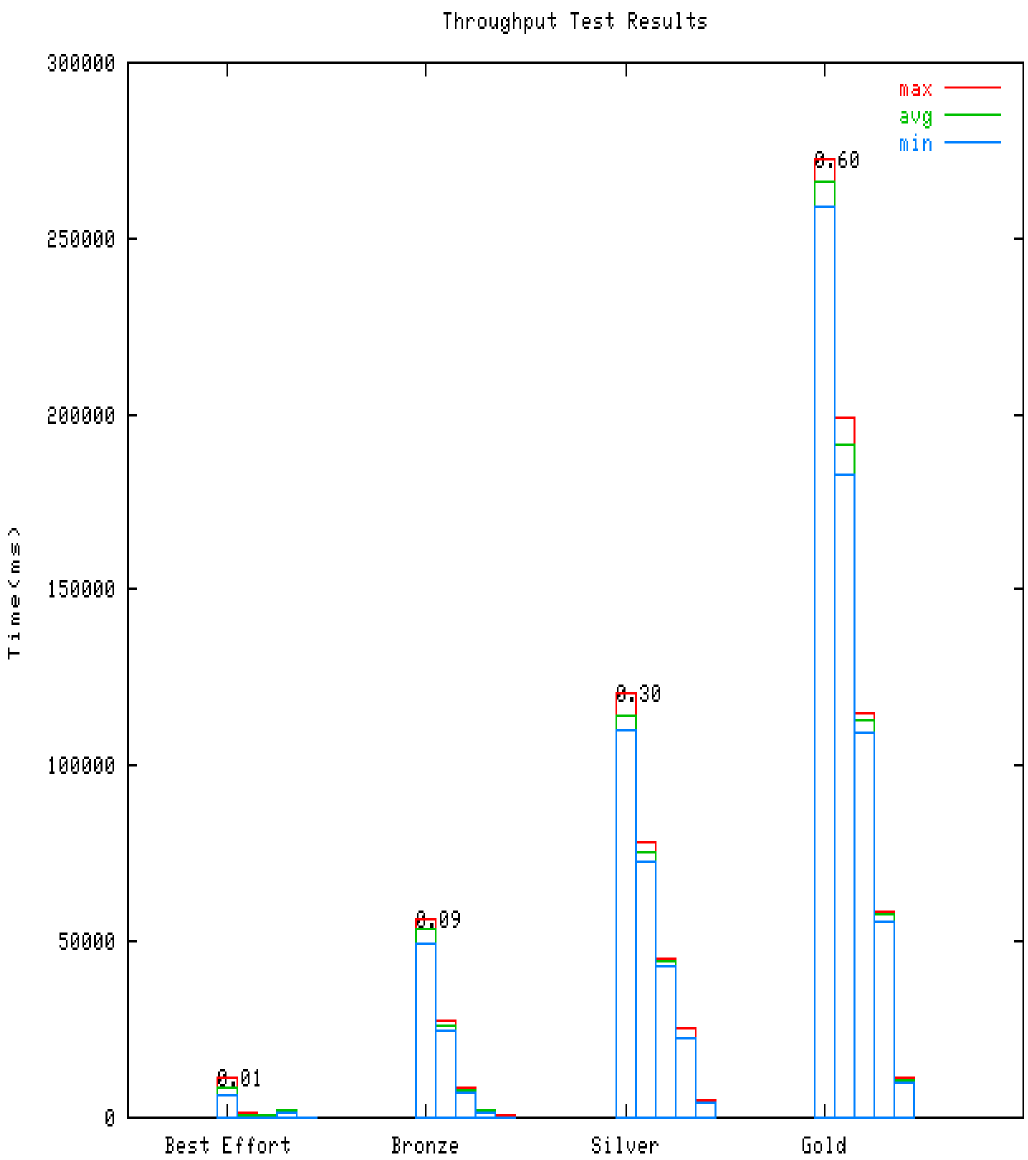

- Measured using Lmbench
  - lat_ctx -s 0 $N,   N=(2..256)
- Scalability: the overhead of Class Fair Scheduler increases at about the same pace as Linux 2.5 Scheduler
- The static overhead (class – linux) varies from 0.14us to 0.63us during the measurement
- Since class selection is O(1), i.e. Independent of #classes, there are no scalability concerns with #classes
- Code optimization might further reduce the static overhead

# SMP / Load Balancing

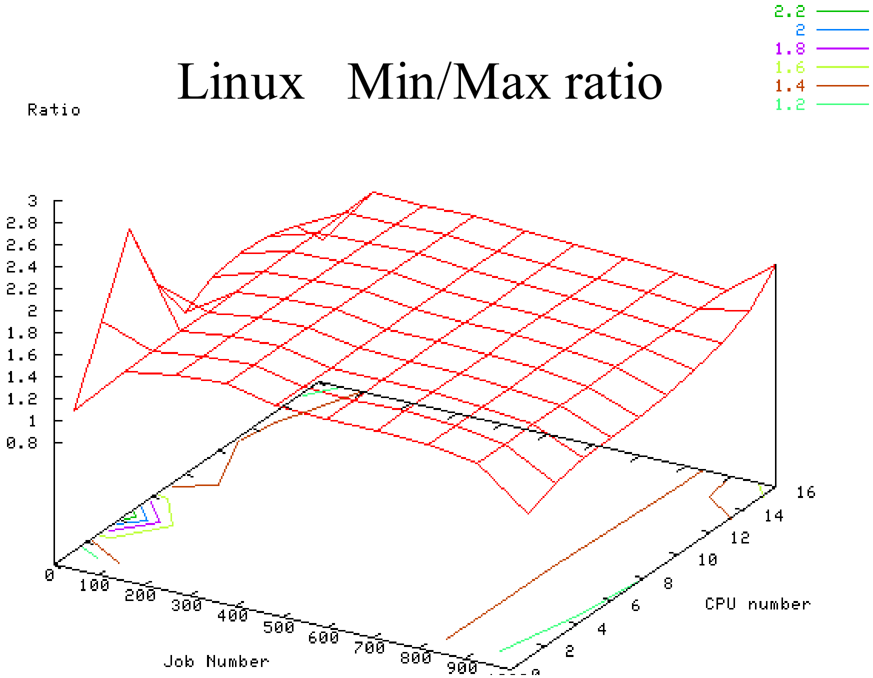
- Achieve global shares per class
- Maintain fairness within class (nice ratios)
- Tasks in same class/nice need similar progress
- Balancing runqueue length insufficient
- Solution: pressure based balancing
- We DO NOT try to attempt to achieve class shares on each cpu
- Progress: ticks/EPOCH
- Estimated progress of class on cpu
  - EP(C,cpu) = $\Sigma$ ts * ia(ts) *(maintained)*
  - P(C,cpu) = EP (C,cpu) / cpu_usage(C,cpu)
  - cpu_usage(C,cpu) maintained by MovAvg
  - Ensure that P(C,cpu-i) = P(C,cpu-j)

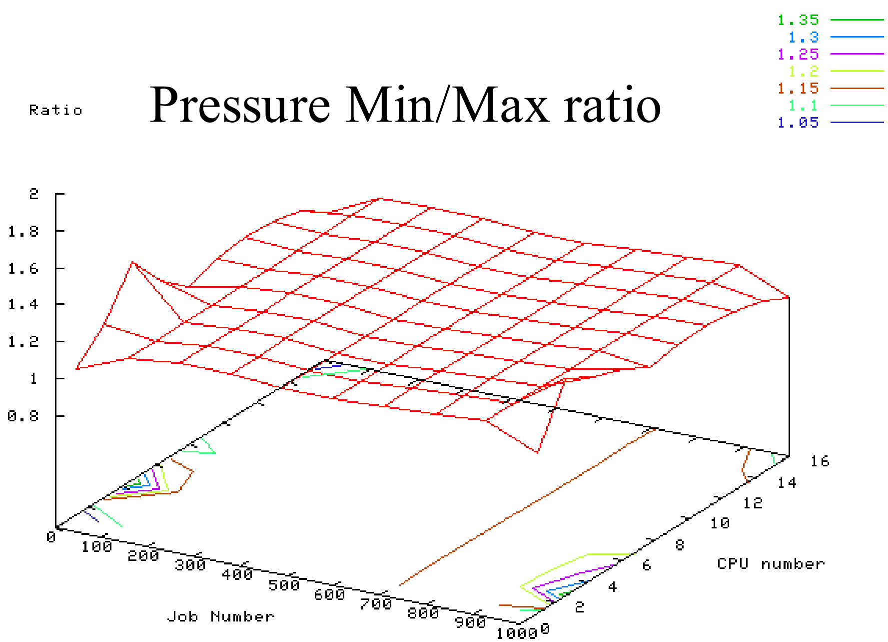


# SMP and Load Balancing




- Simulation Result
  - (8 CPU, 300 CPU bound jobs)
  - Similar test setting as throughput test
  - Propotional sharing among classes maintained (60:30:9:1)
  - CPU time of tasks (same class,different nice) is propotional to time_slice
  - Tasks (same class, same nice) receive roughly the same service  (diff < 4%)




# Load Balance (cont.)

- Compare load balancing based on pressure (as describe before) vs runqueue length (used by Linux)
- Define fairness as: the max cpu time vs the min cpu time received by processes with the same class and same nice value.
- The figure shows the fairness achieved by linux vs by pressure under different workload and number of cpus
- Pressure is a better approach in general. The difference can be larger when worloads are interactive.

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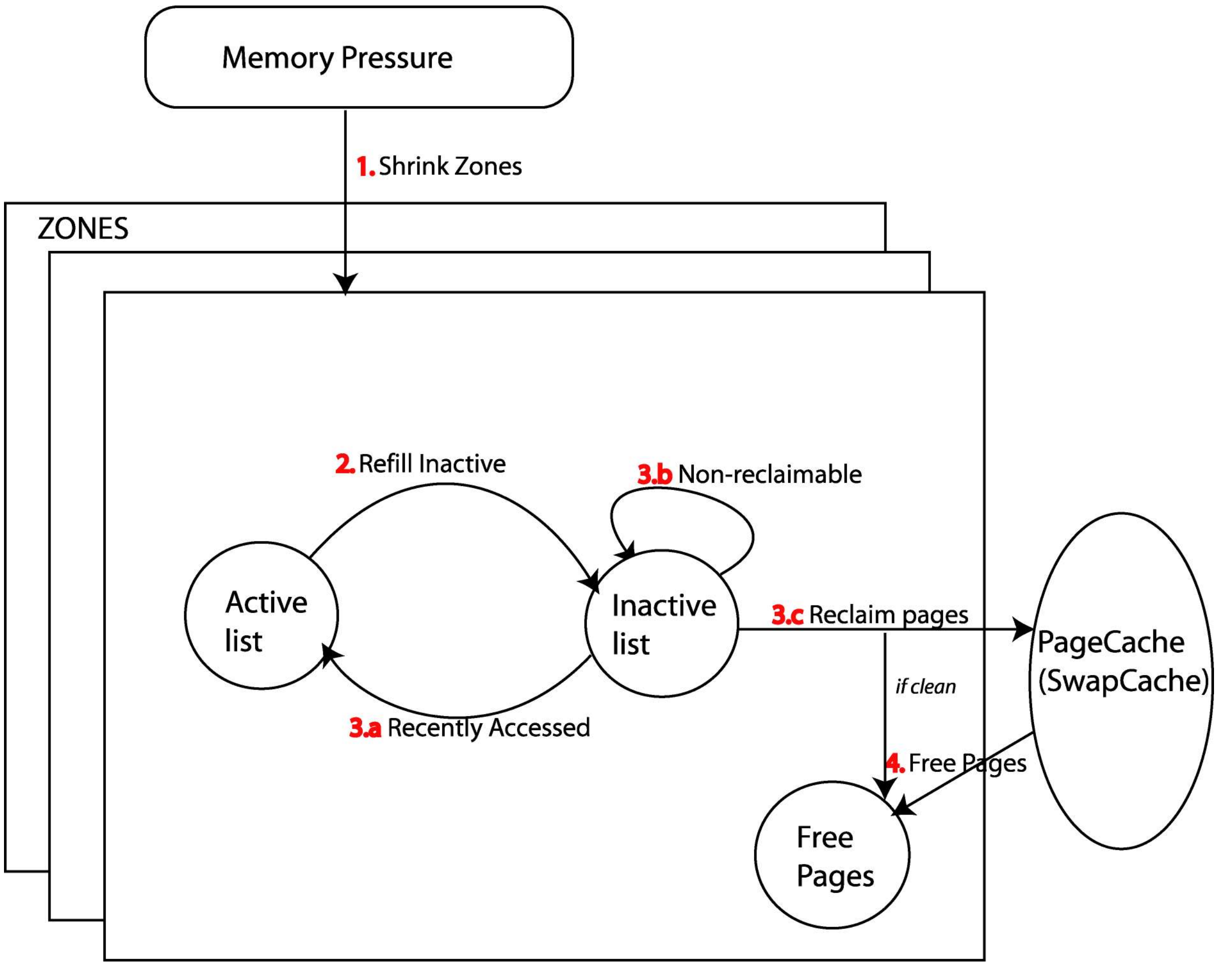
# Controlling Memory

- Average number of physical pages resident per-class
  - Does not correspond to page fault rate control
- Control points
  - Page allocation
    - Strict control similar to per-mm rss enforcement
  - Page reclamation
    - Looser control only done under memory pressure

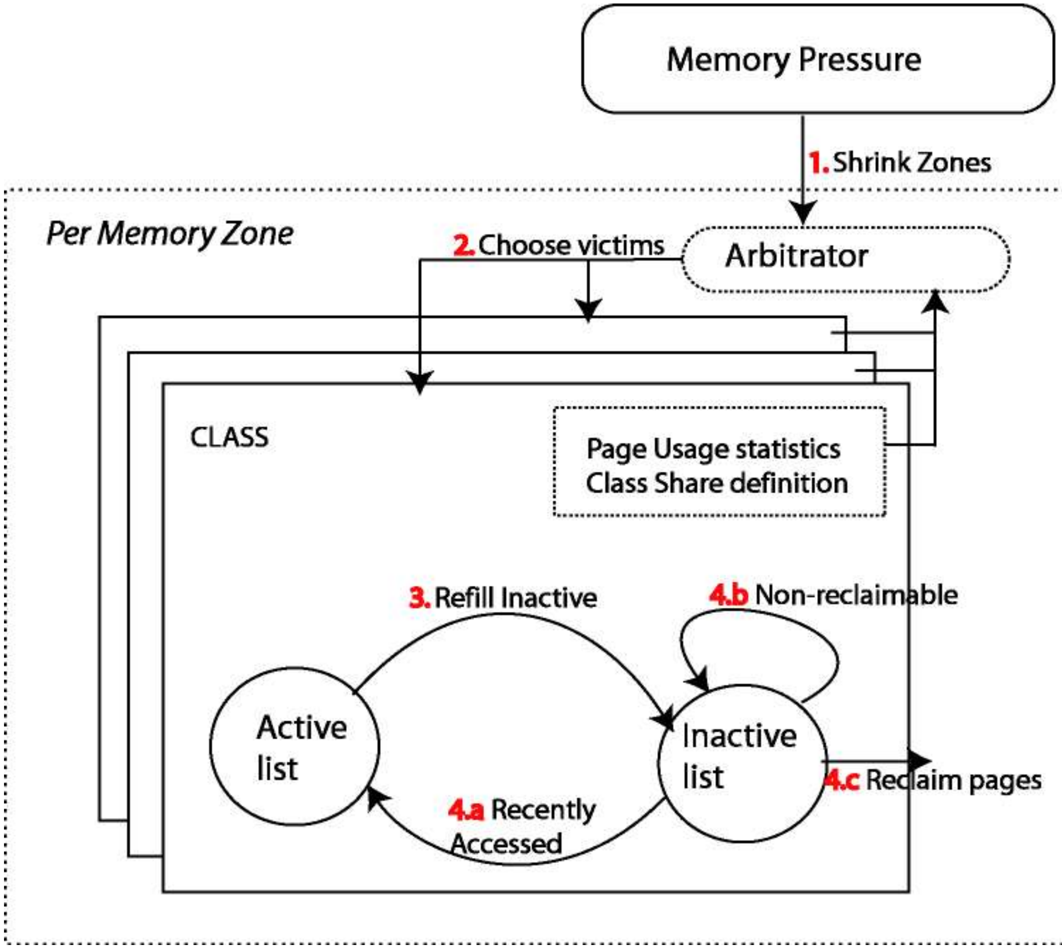
# Linux 2.5 Page Reclaimation



# CKRM Memory Control Design

- Share is #maximum physical pages used per class
  - hard/soft,  min/max variants also possible
- Only control page reclaimation
  - classes can exceed shares if no memory pressure
- No distinction between over-share classes
  - reclaim as many pages as needed by shrink_cache()
- Use global active/inactive lists
  - maintains global LRU order
  - overhead of  repeated scans of under-share pages

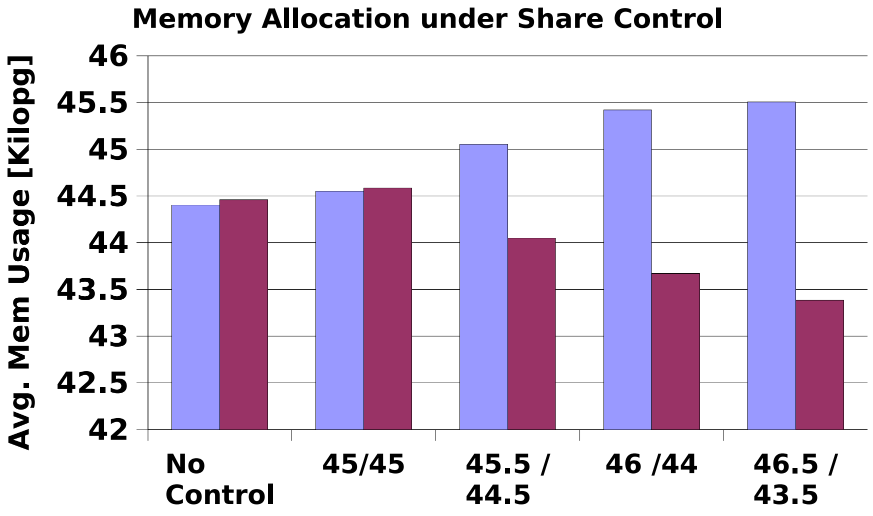
# CKRM Memory Control Implementation



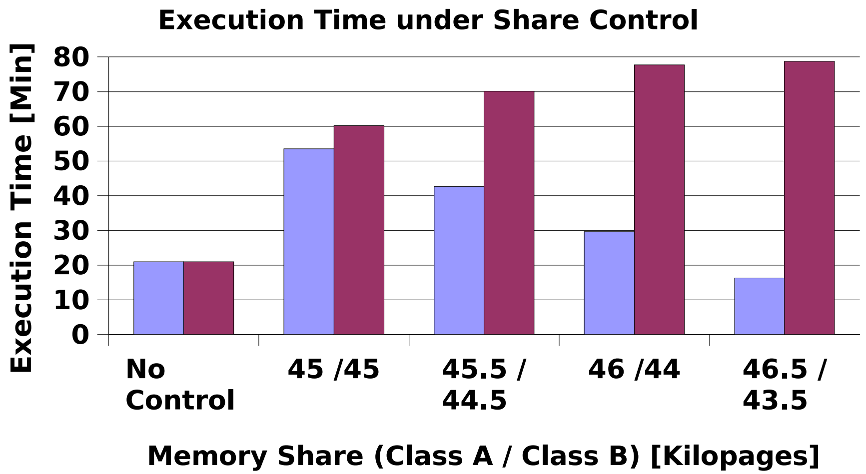
# Memory Control Testbed

- Testbed
  - Uniproc: 2.4 GHz P4 uniprocessor, 512 MB memory
  - SMP: 8-way 700MHz PIII Xeon, 3 GB main memory
- "173.applu": SPEC CPU2000 Benchmark
  - Avg working set size ~ 184 Mbytes (46 Kilopages
  - Execution time (uniproc) ~ 7.85 minutes
- Microbenchmark
  - Working set size, memory access pattern determined by exponential probability distribution
  - Smoother degradation with memory share reduction

# Uniproc, 368M memory, “173.applu”



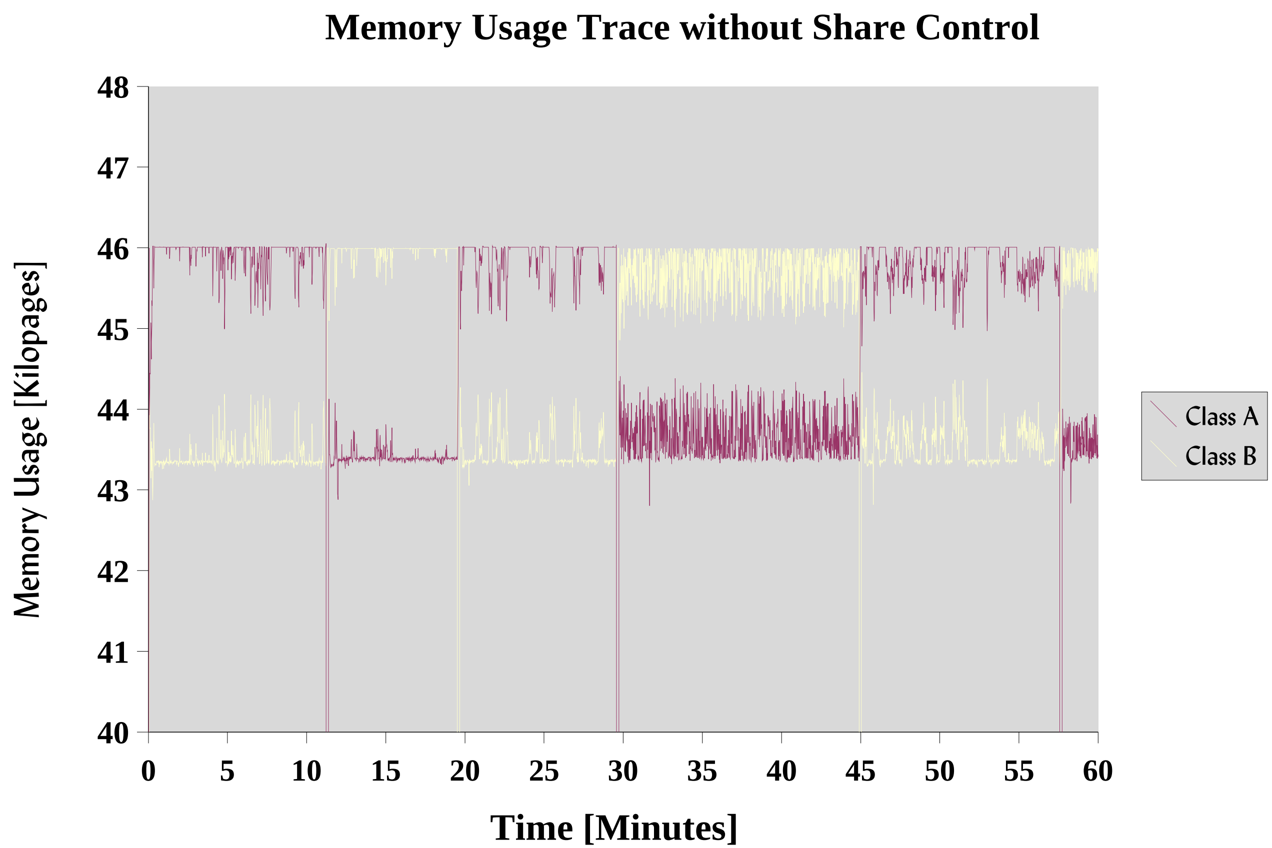

- Two classes, one app per class
- Two scripts run each class/app in a loop for ~10 hrs (~20 minutes per run)
- 92 Kilopages needed, 90 available
- Memory usage for each class collected and averaged over entire expt
- Execution time = avg. for each run




**Observations**

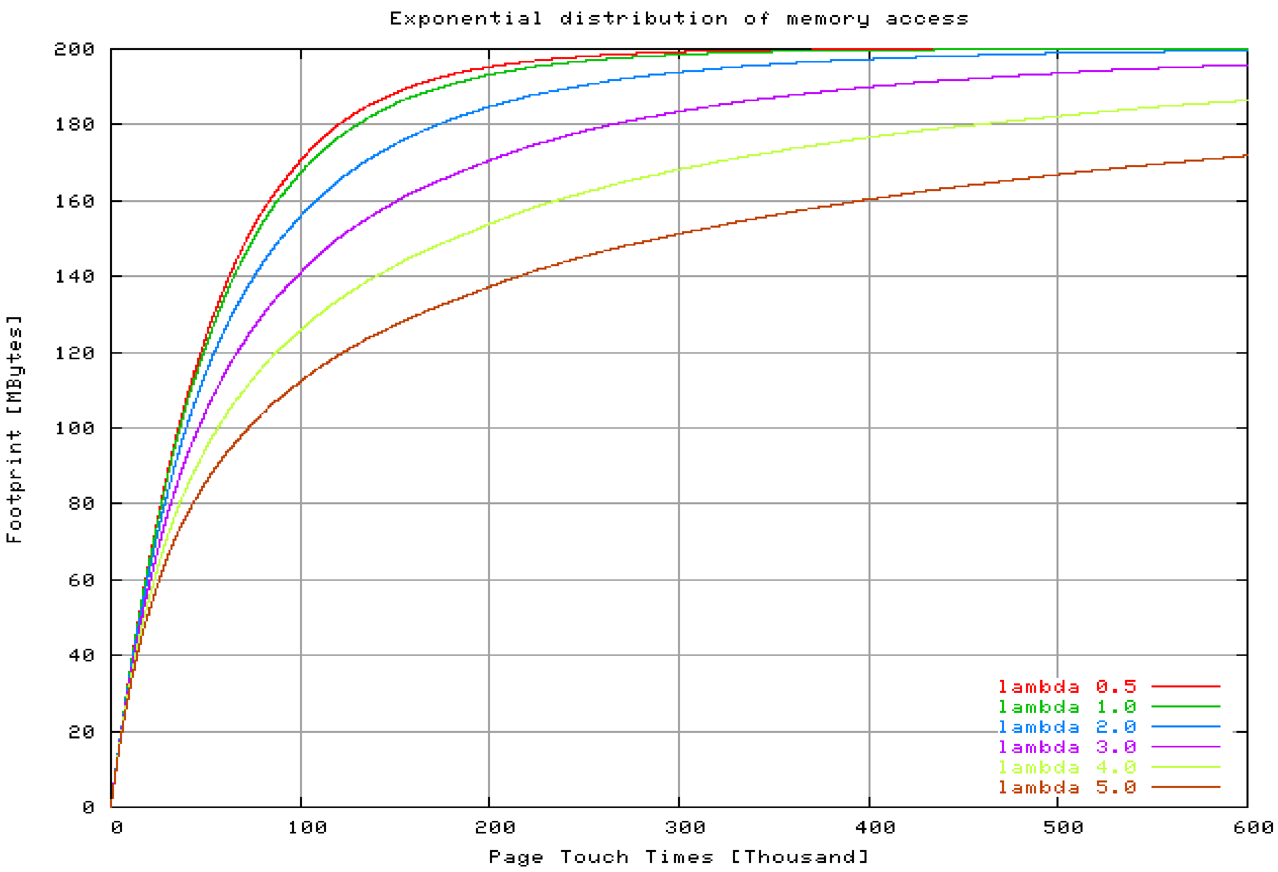
- Share settings respected
- Execution time decreases by giving more memory share
- Degradation in execution time from no control to equal share case
  - ➔ effect of page faulting on CPU scheduling.

# Memory control affects CPU scheduling



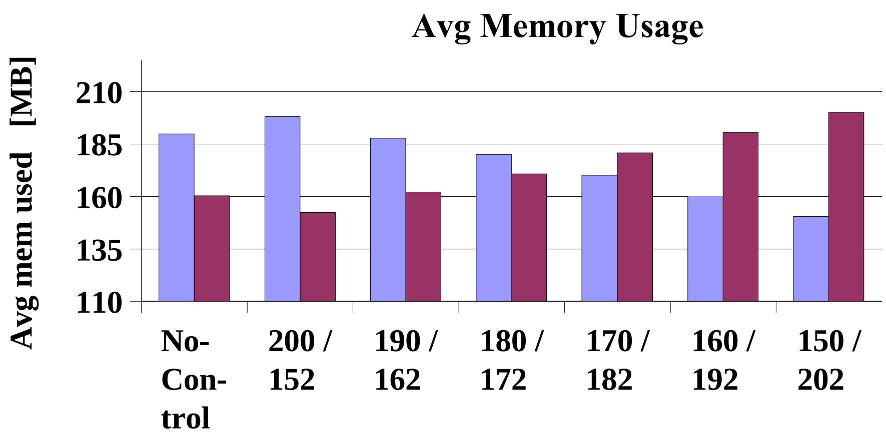

- Measure memory usage over time for no control case
- Class B, starts second, gets much lower share, makes less progress due to increased page faults
    - improves after first run of Class A finishes
- "Batching" behaviour improves total execution time over equally penalized (equal share) case

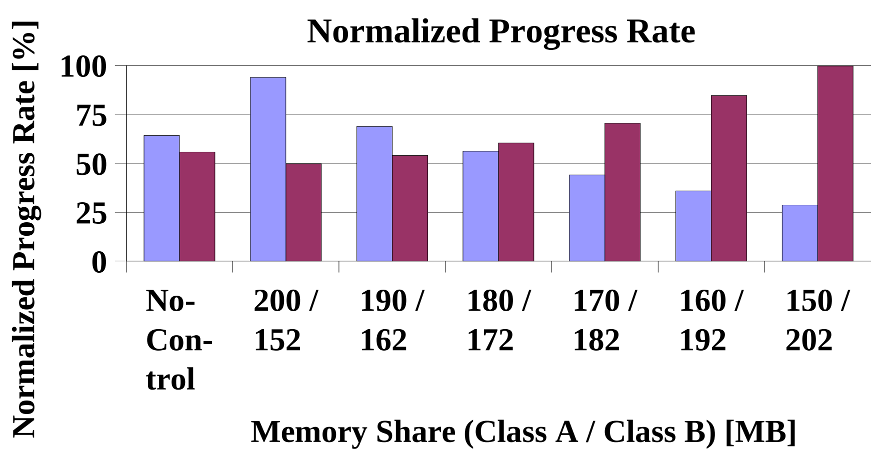
# Artificial Workload, RSS of 200Mbytes




- Exponential probability distribution
  - Memory access pattern
  - Memory footprint
- Cumulative footprint size with increasing number of page accesses shown above

# SMP, 372M, Microbenchmark



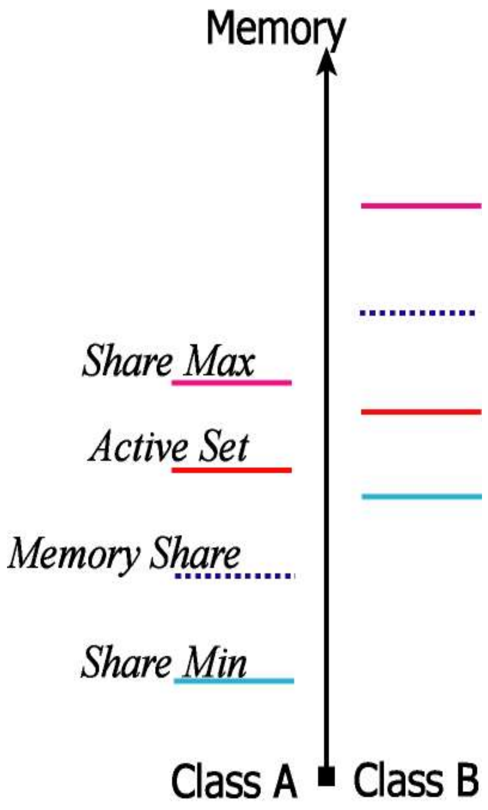




- Two classes, one microbenchmark per class
  - Class A accesses memory twice as fast as Class B
- ~400 MB needed, 352MB available
- Memory usage and progress measured every 3 seconds, averaged over entire expt
- Progress rate normalized across classes

**Observations**

- Share settings respected
- Progress rate increases with more memory share
- System default behaviour and 192/162 share settings show very similar memory share and progress rate
  - Reduced effect of memory share on CPU scheduling on SMP

# Advanced Page Reclaim Policies




- Memory share
  *Memory distribution among classes*
- Share max
  *Upper bound of memory usage under memory pressure*
- Share min
  *Guaranteed memory usage*
- Active set size
  *Real usage by each class*
  *Measured statistically by causing soft faults*
  *Can be used to tradeoff under, over share classes*

- Order of choosing victim classes
  *First, classes above share max.*
  *Second, classes having idle pages (Usage>AS)*
  *Third, classes above memory share*
  *Fourth, classes above share min*

# Shared Memory Control

- Pages shared by multiple classes complicate accounting
- Shared address space
  - Create class hierarchy with notion of parent classes
  - Group shared pages into system-defined classes, each with multiple parents
    - each parent corresponds to a regular policy-defined class
  - Apportion page reclamation between system-defined class and parent classes appropriately
- Page cache, memory mapped files, shmem
  - Assign pages to (first, most recent, max share) class
  - Treat pages similar to shared address space case

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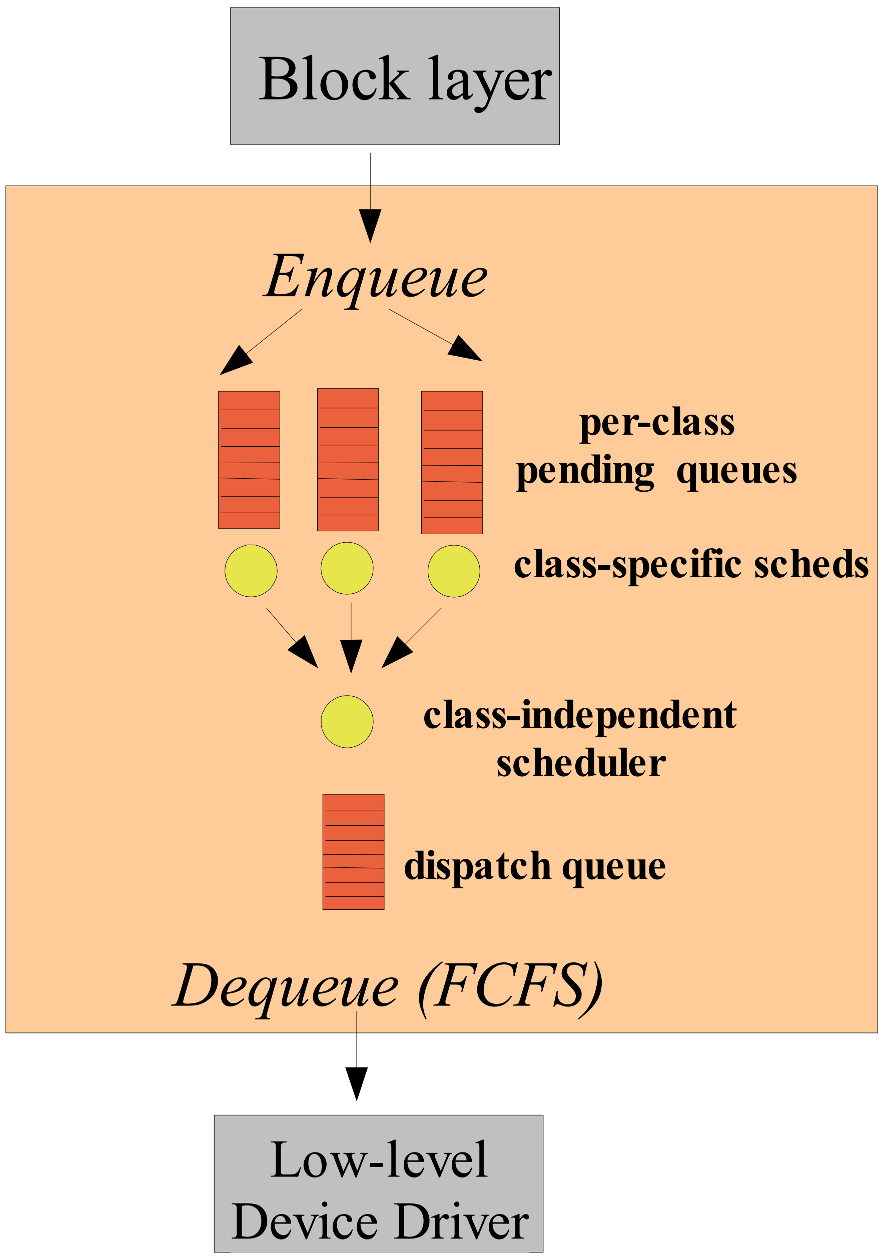
# Controlling I/O

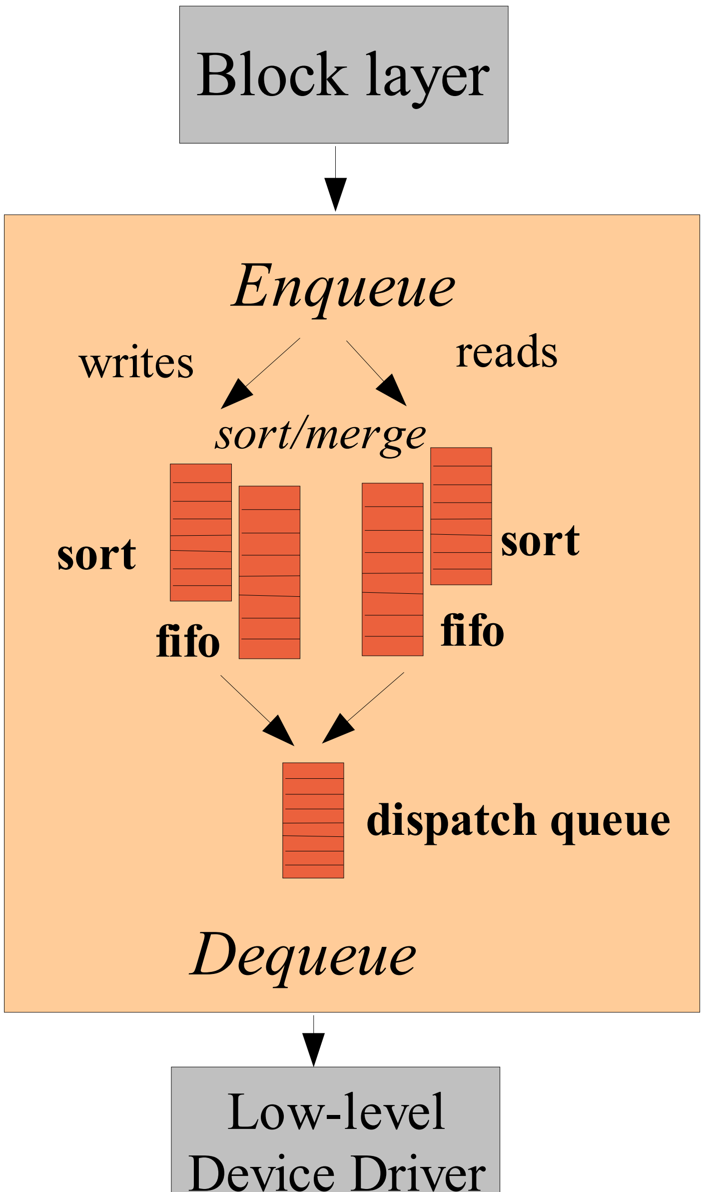
- I/O bandwidth consumed by each class
  - Bandwidth measured by #bytes of I/O transfers initiated in either direction
- Per-disk shares
- Current design changes I/O scheduler (iosched)
  - Regulation at layers above (filesystem and VM) or below (device driver) also possible
  - iosched changes are simpler and good enough

# Cello I/O Scheduler



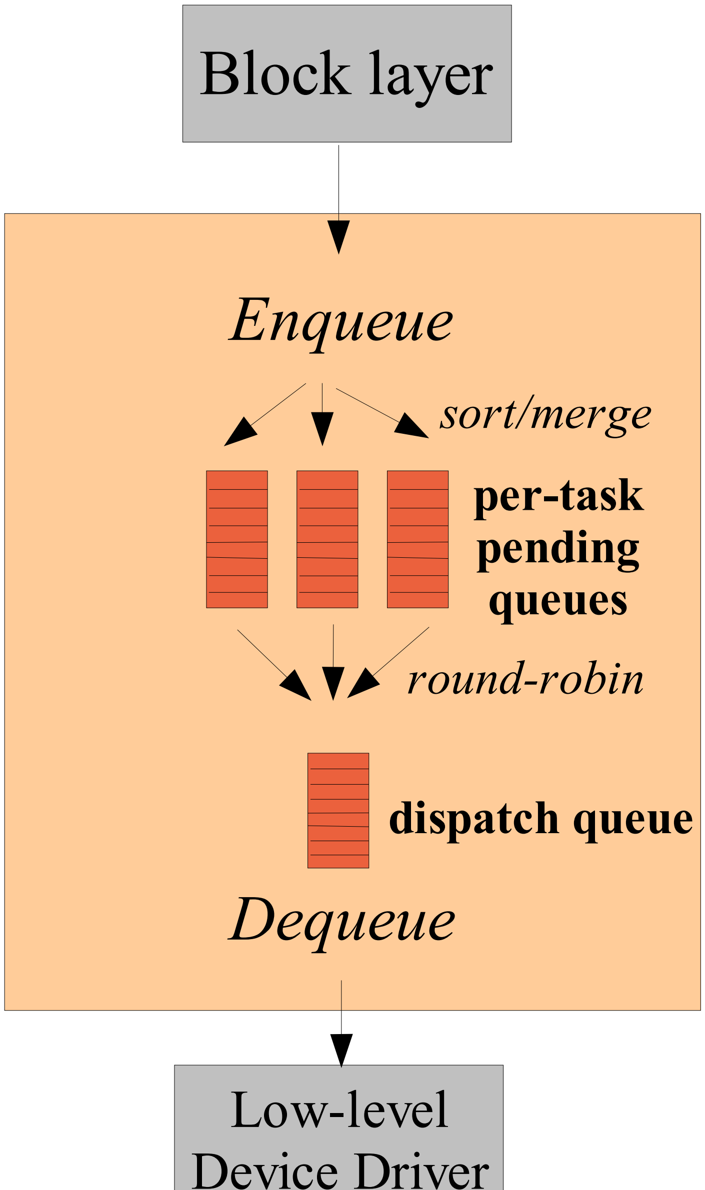

- Two-level disk scheduler
  - Separate bandwidth from ordering
  - Work conserving
- Class-independent, coarse grain
  - Bandwidth allocation
- Class-specific, fine grain
  - Ordering within class
  - seek-optimizing, EDF
- Good results on Solaris
  - Linux implementations unstable or in progress

# Deadline I/O Scheduler




- Improves average read response time
  - Disk utilization secondary
- Separate read/write input Q's
  - Requests sorted by sector (*sort*) and deadline (*fifo*)
- Batched transfers to dispatch queue
  - reduce seek overhead
- Implementation similar to Cello

# CFQ I/O Scheduler

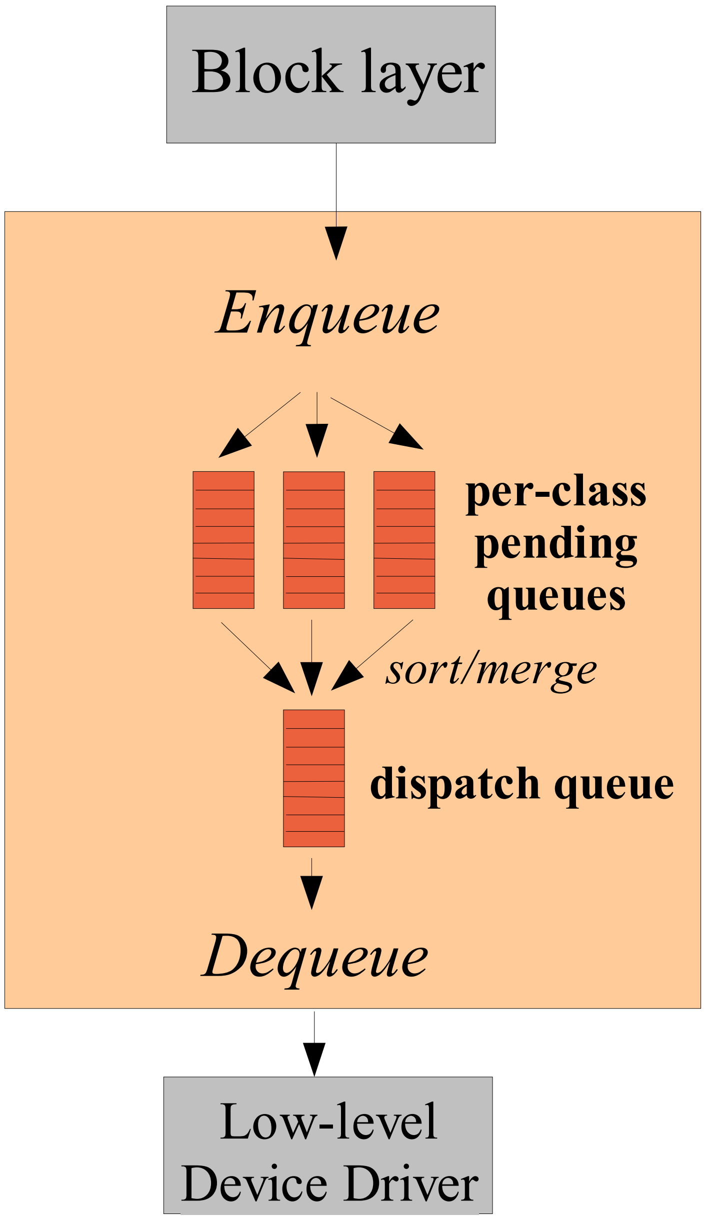



- Precedence of fairness over throughput
  - Each task has equal share
- Per-task request queues
- Dequeue function implements fairness
  - Roundrobin through non-empty queues
- Simple changes can implement priorities for dequeuing

# I/O control requirements

- Weight/priority of I/O request submitter takes precedence over disk utilization
  - Already happening in 2.5 I/O schedulers
    - Anticipatory – per-task performance
    - Complete Fair Queuing (CFQ) – fairness
- Associate I/O request with class of submitter, not task/user
  - Weight of request = weight of submitting class
  - task/user based treatment can be done using classes

# Costa I/O Scheduler




- Variant of Cello/CFQ
- Per-class input Q's
  - System queue for urgent/important requests (VM writeout)
- Deque requests using class weight
- Adding deadline
  - sort/fifo lists for each class
- Adding anticipation
  - service another request from same task, adjust class share
- Implementation planned

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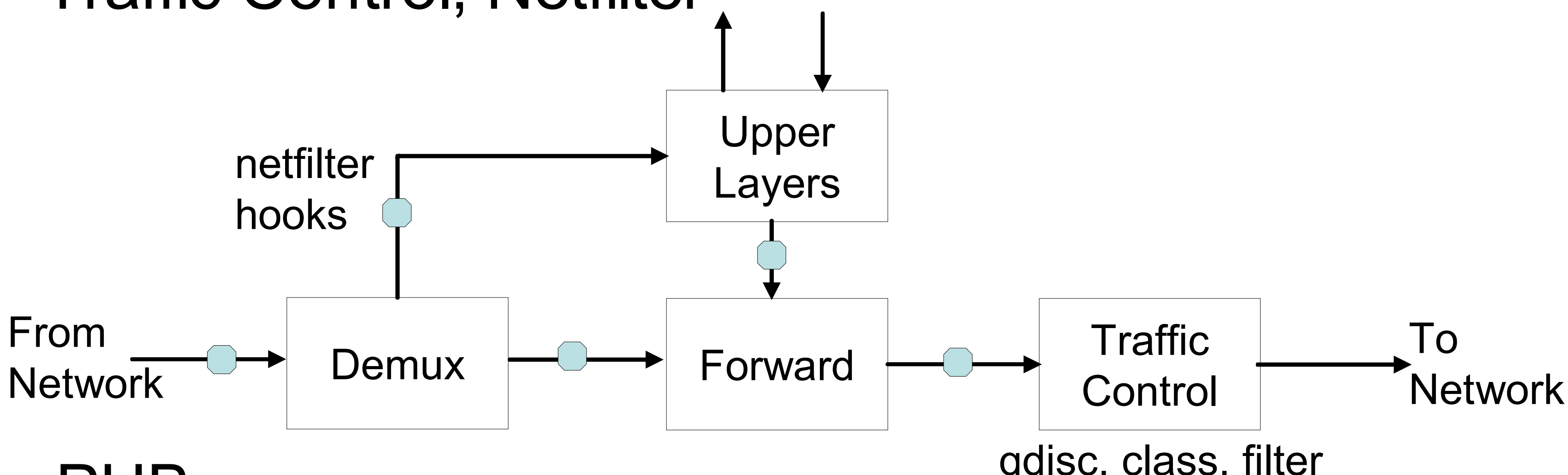
# Network QoS

- DiffServ support in Linux provides Internet QoS
- Traffic Control, Netfilter




- PHBs
  - classifier, marker, shaper/policer, meter
  - Implemented by traffic control / netfilter
- End server QoS support in Linux ?

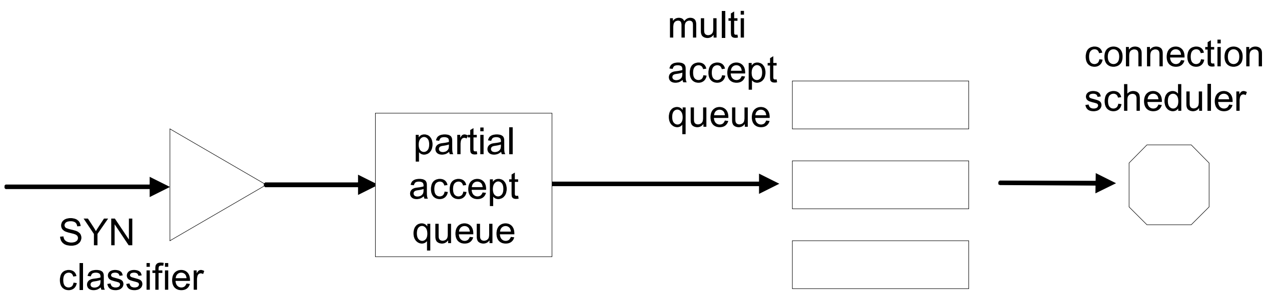
# Inbound Network Control

- Motivation
  - Incoming connections initiate resource consumption
  - Head-of-line blocking of high priority connections under network load
    - Persistent connections exacerbate the problem
  - Application level control not enough under high load
- Prioritize acceptance of incoming connections
  - Classify connections using iptables or during in-kernel application protocol processing
  - Reorder socket accept queue

# Prioritized Accept Queues

- Classify using (local, remote) x (IP, port)
  - Iptables rules defined
- Split single accept queue into prioritized queues
  - low priority conn requests moved back to SYN queue if accept queue full
  - SYN policing to avoid starving low prio conns
- Shown to prioritize connections effectively
- Drawbacks
  - Classification hard in presence of proxies and multiple classes on same remote host

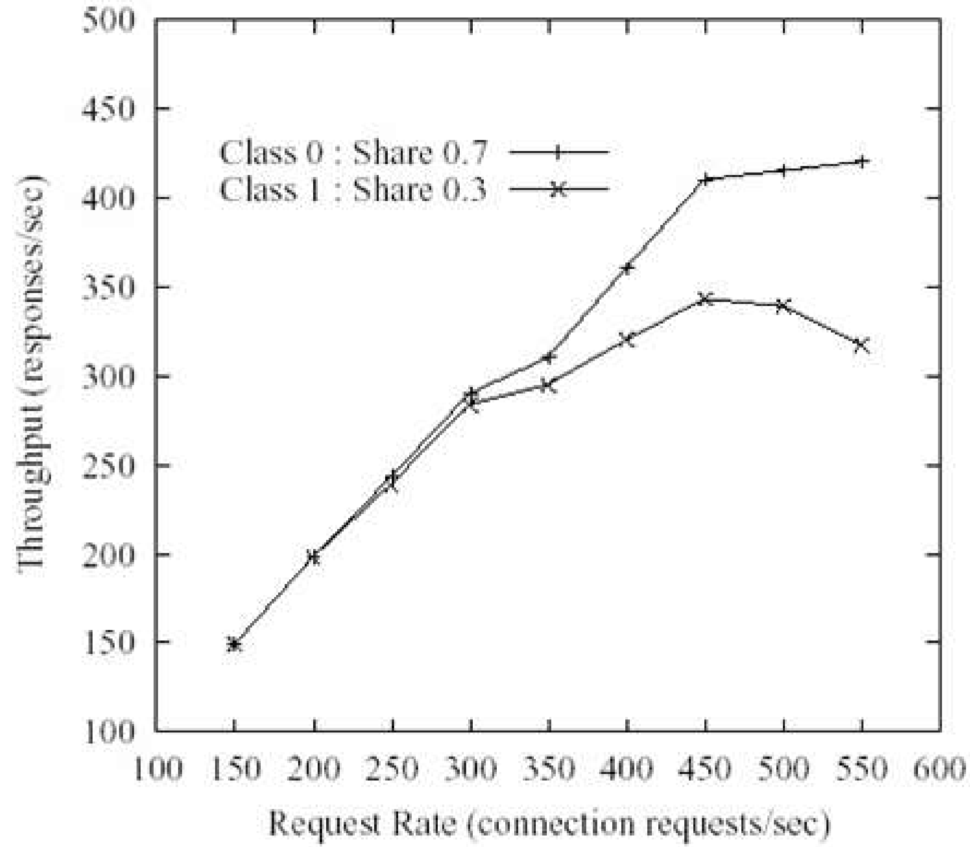
# Proportional Share Scheduling (PSS)




- Variant of PAQ with weights instead of strict priorities
  - Connections accepted from each queue in proportion of weight
- Only controls distribution, not amount of available bandwidth

# PSS Experimental Results

- Httperf clients, Apache web server




- Class 0 : Class 1 = 7:3
- From 300 reqs/sec, acceptance follows the weight

# End Server Connection Control

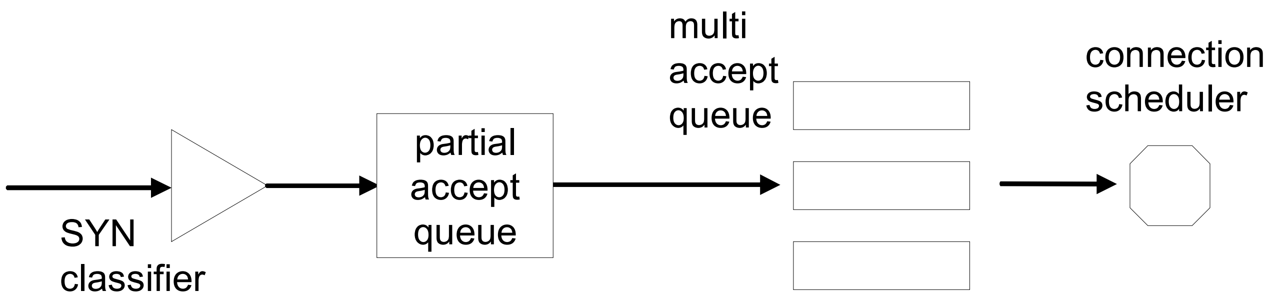
- Head of Line Blocking
  - When service time of a connection is high (e.g. persistent connection)
  - High priority connection requests may block indefinitely
- Multi Accept Queues

  [Voigt01] Priority Accept Queue

  http://www-124.ibm.com/pub/qos/paq_index.html

  [Pradhan02] Proportional Share Accept Queue

  design by IBM LTC (Nivedita, Vivek)



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# Conclusions

- There is a need for class-based control over all physical resources managed by the kernel
- A design and implementation exists for CPU and Memory
  - achieves major objectives
  - small modifications to existing code
- I/O and inbound network in development
- Ideal candidate for a 2.7 feature

# Getting involved

- Open source project at Sourceforge
  - http://ckrm.sf.net/
- Birds of Feather session
  - 30 minutes, same room
- Participation and feedback invited

# CKRM:

# Class-based Prioritized Resource Control in Linux

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