Improving Linux resource control using CKRM

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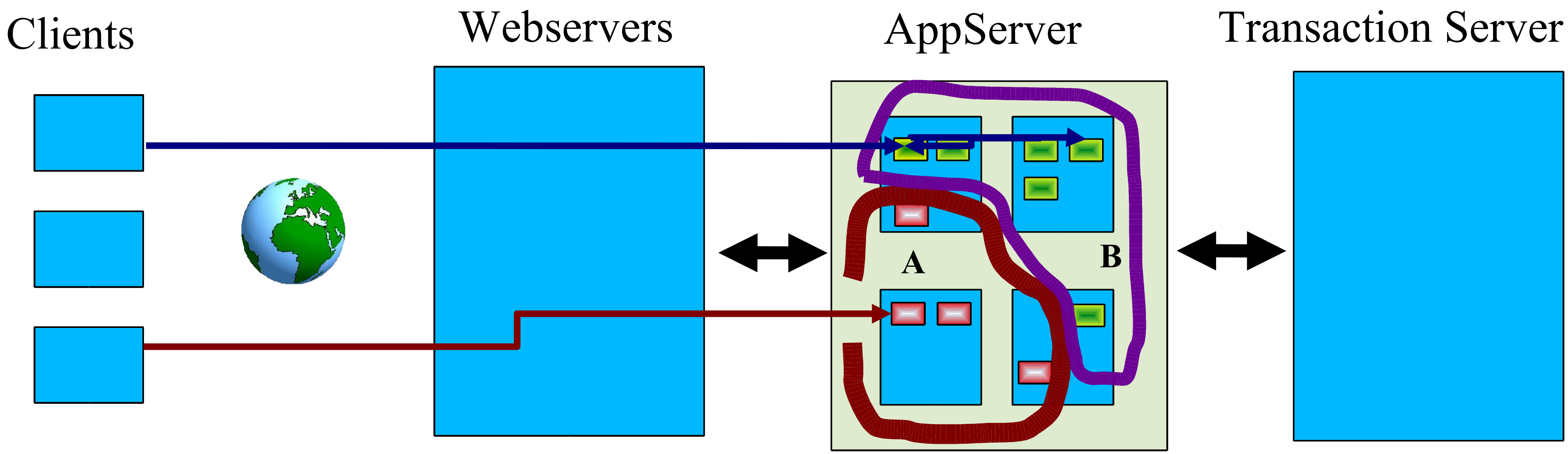
Outline

- Recap
  - Motivation
  - Architecture
- New since 2003
  - Core redesign
  - Resource Control Filesystem
  - Hierarchies
  - Schedulers
- Future Work

Workload Management Requirements

- Modified resource principal is a group of processes (class)
  - User-defined
  - Dynamic
  - Visible to OS kernel
  - Support for automatic classification of new processes
- Privileged user defines class entitlements/shares
  - Generally CPU, virtual/real memory
  - I/O, network less common but useful
- Role of OS Kernel
  - enforce shares
  - monitor, export class usage
- State of art for high-end Unixes and Windows (?)
  - HP-PRM/WLM, AIX WLM, Solaris, Tru64

Usage 1: Enterprise Servers



- Class determined by
  - who, what, where
  - any workload attribute (not all traditionally visible to kernel)
- Different QoS for each class:
  - Response time, bandwidth
- Class boundaries change rapidly

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

Usage 2: Shell server

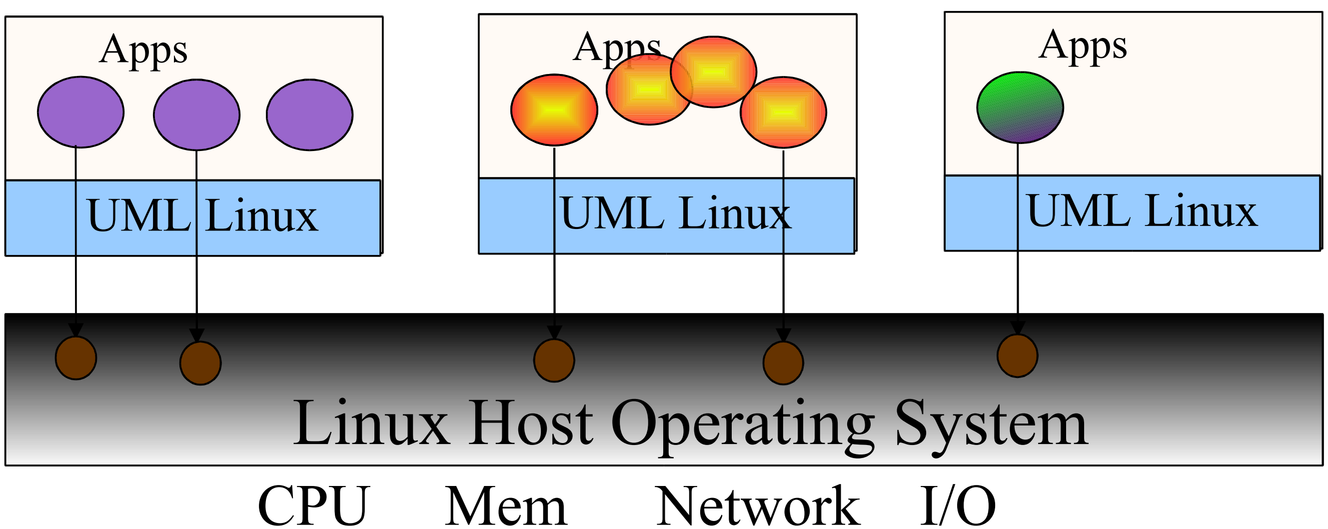
- University shell server with different users
  - Students: Low
  - Staff/postdocs : High
  - Accounts/Backup: Batch/Background
  - OS Class Projects, Physics simulations
- Resource shares set from PAM module at login
- Email processing
  - Charge to user being processed
  - Automatic classification based on uid/app name

Usage 3: Desktop

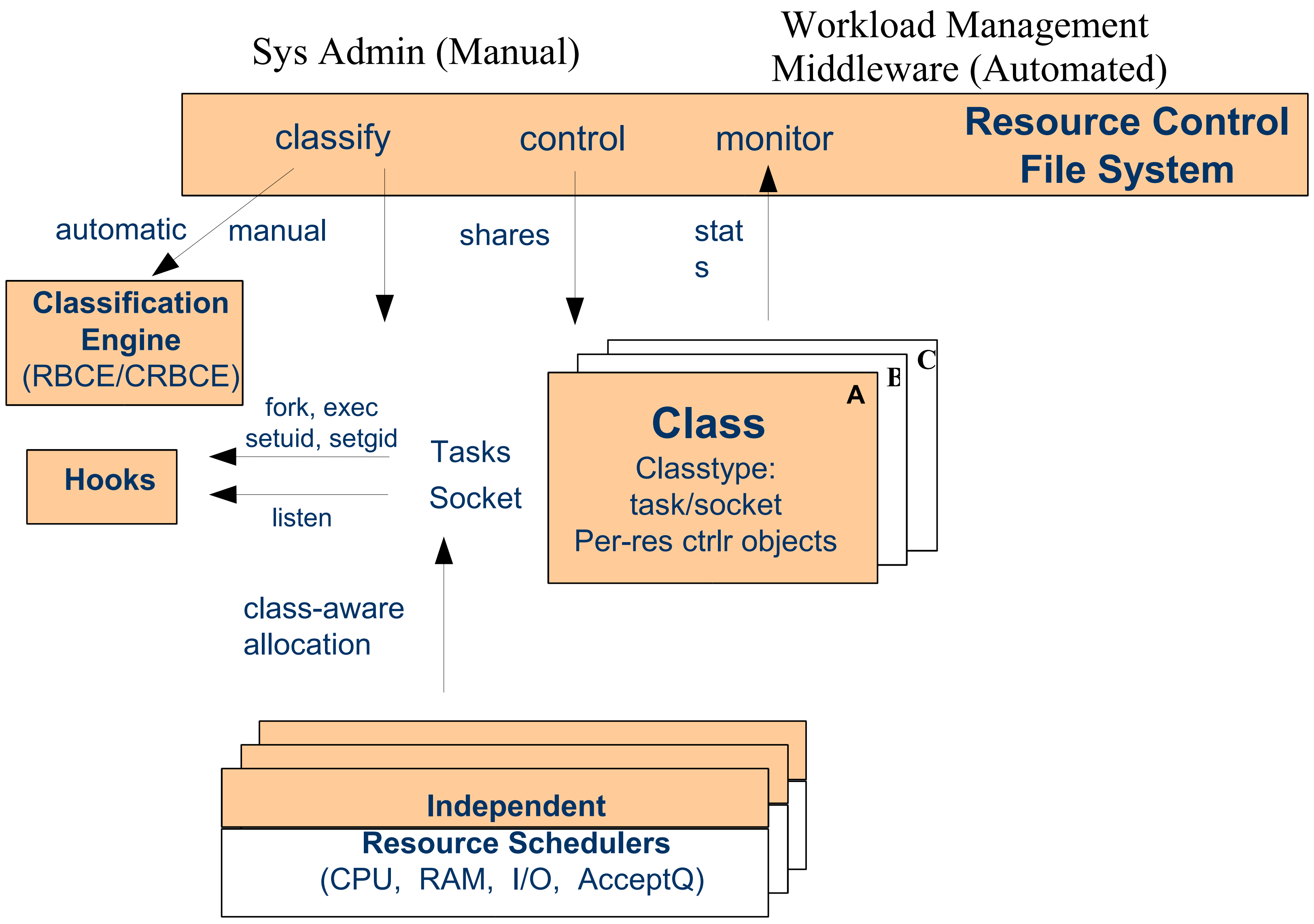
- Protect apps from each other
  - X
  - Xmms
  - Shell
  - Mozilla
- User level control over app-class shares
  - Done automatically by user's GUI
- Requirements
  - Simple interface
  - More tolerance for share enforcement inaccuracy
  - Little need for monitoring

Usage 4: UML/vserver Virtual Hosting

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



CKRM Architecture



CKRM Main Components

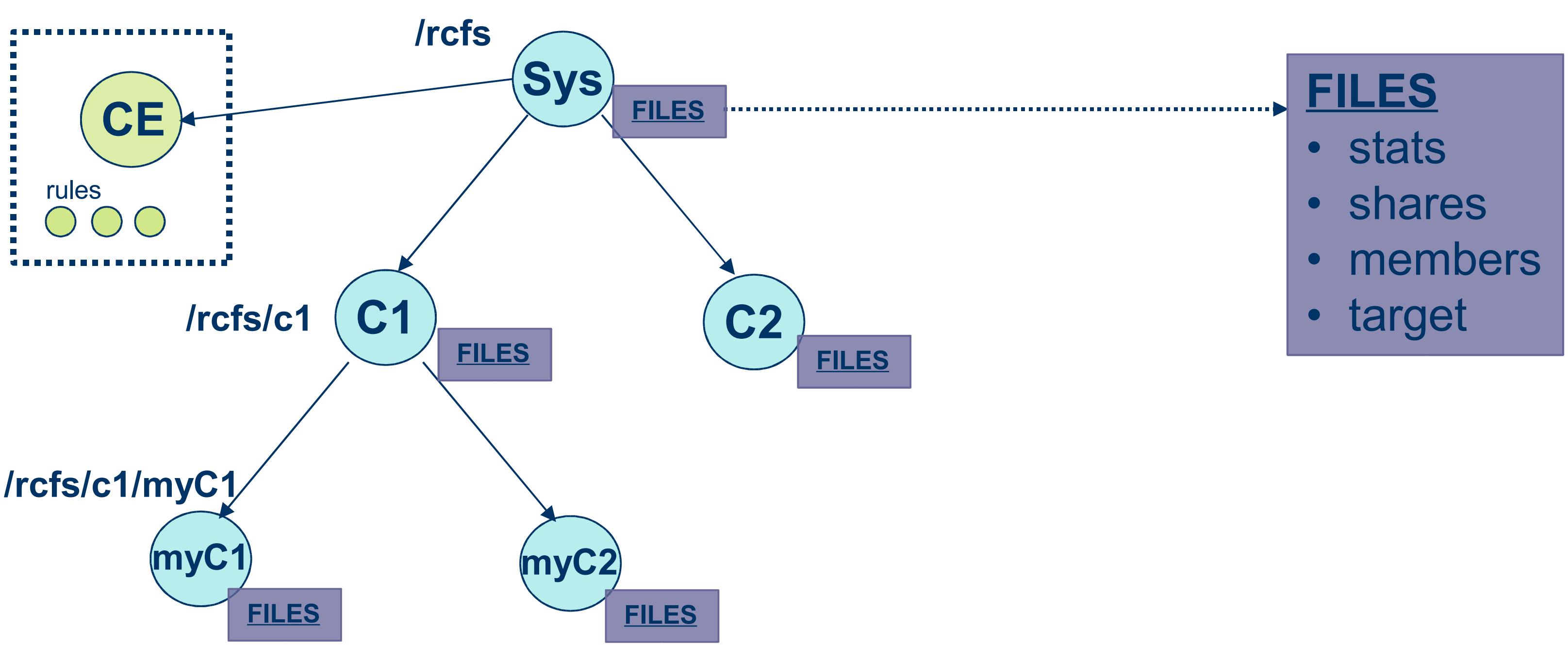
- Classtypes
  - Define kernel resource object to be grouped
  - Independent dimension for all other components
- Classes
  - Hierarchical grouping of kernel resource objects
  - Associated shares of managed resources
- Classification Engine
  - Policy-driven assignment of kernel objects to classes
  - Notifications of kernel events to user level
- Resource Control Filesystem
  - User API to CKRM
- Resource Controllers
  - Class-aware enhancements to existing Linux schedulers
  - Physical resources (CPU, Physical Memory, Disk I/O, Socket connections)
  - Virtual resources (number of tasks)

Modular design

- Classtypes can be independently included
  - One or more of task_classes, socket_classes
- Classification Engine completely optional
  - manual classification always available
- Resource Control Filesystem interface
  - replaceable with system call interface if necessary
  - Filesystem implemented as a loadable module
- Completely independent controllers
  - Independent data structures, kernel configuration
  - Independent in-kernel operation
    - May not be desirable in long term
    - Coupling possible through user-level WLM components
  - Decouples acceptance of scheduler patches in mainline kernel

User API (RCFS) Overview

- Directory = Class
  - Filesystem hierarchy ~= Class Hierarchy and namespace
  - /path/to/class represents the unique class name
- Virtual files = Class attributes
  - Created automatically
- Standard filesytem operations = CKRM functional API
  - mkdir/rmdir = create/delete class
  - read/write virtual file = get/set attributes (shares, stats, config,classification rules,…..)
  - File permissions/ownership used to restrict/delegate access to operations

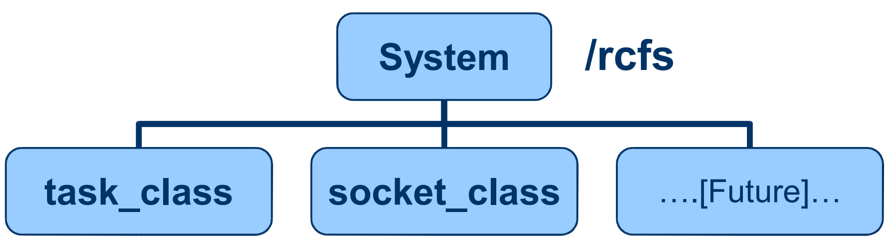


CKRM Core Overview

- Classtypes
  - Define kernel object being grouped
- Classes
  - Group of kernel objects
- Kernel hooks
  - CKRM code executed at significant kernel events such as fork, exec, setuid, setgid, listen

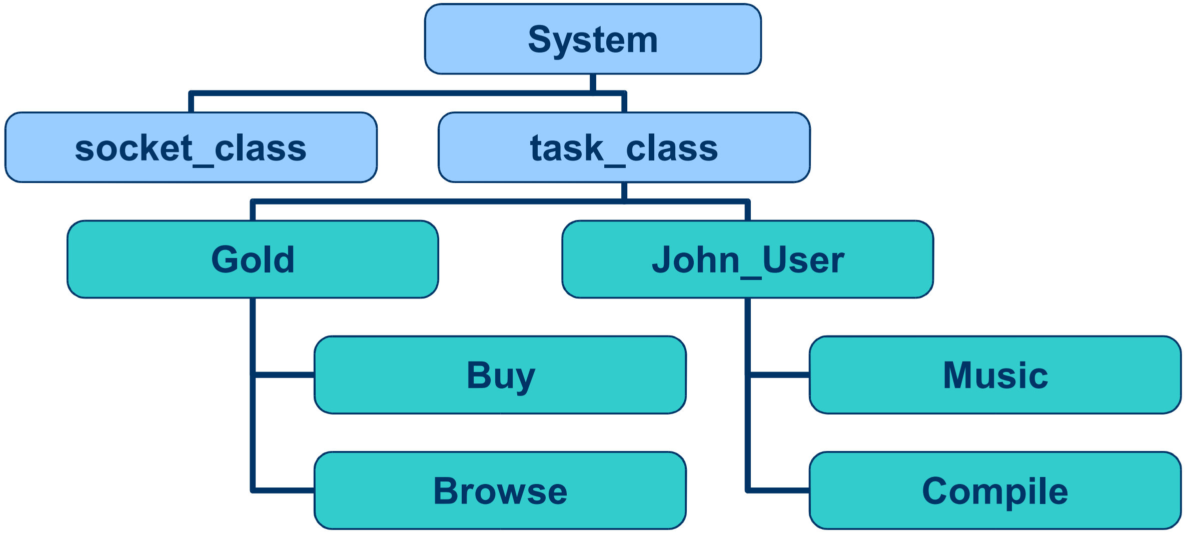
Classtypes

- Define kernel object being grouped
  - Currently tasks (task_class), listening sockets (socket_class)
- Independent dimension for other components
- Each classtype has an associated
  - Hierarchy of classes
  - Set of resource controllers
    - Mutually exclusive across classtypes
  - Classification engine rules
  - Directory in filesystem
    - Automatically created when classtype configured



Classes

- Group of kernel objects
- Associated shares (lower and upper bounds)
- Hierarchical to allow further subdivision of resources
  - Top Level shares controlled by privileged user, lower levels can be delegated
- Manifest as directories in /rcfs
  - Filesystem hierarchy under classtype mirrors class hierarchy



Classification

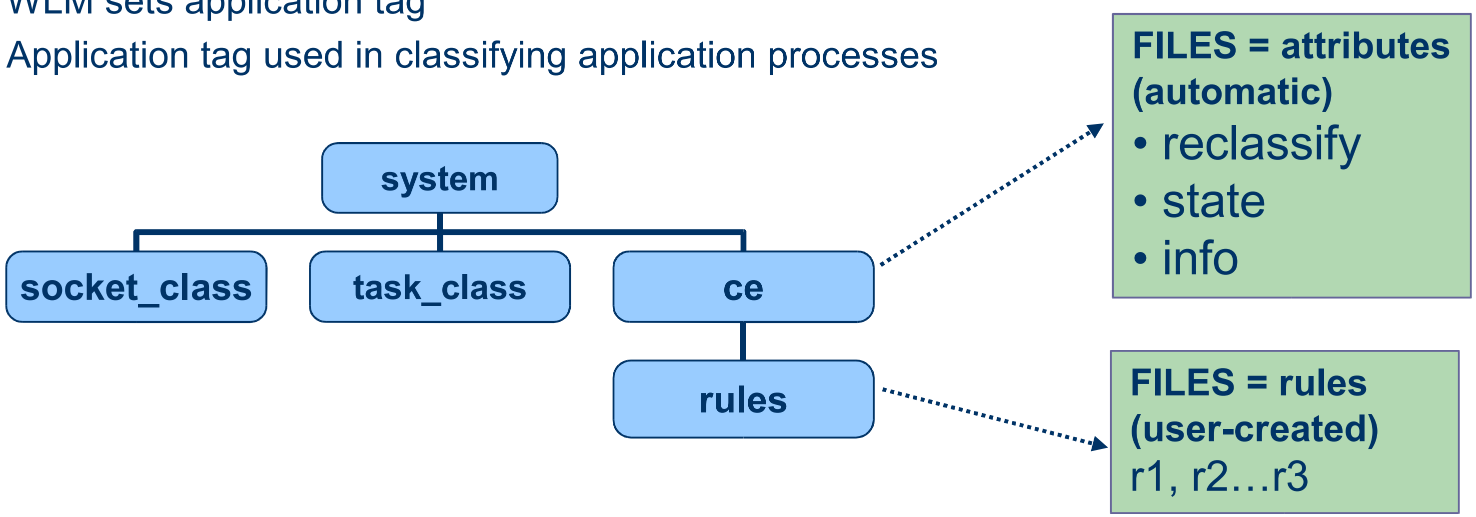
- All kernel objects managed by a classtype need to be in some class
  - Default class always present for each classtype
  - Objects inherit parent's classification unless manual/automatic classification done
- Manual classification
  - echo "<object identifier>" > /path/to/class/target
  - echo "1324" > /rcfs/taskclass/tc1/target
    - Classifies task with pid=1324 into tc1
  - echo "127.0.0.1/80" > /rcfs/socket_class/nc1/target
    - Classifes port 80 of ipv4 address into nc1
- Classification Engine (CE) assists in automatic classification
- Automatic classification points
  - Conceptually any point where the kernel object's attribute changes
    - CKRM implements a useful subset which can be extended as need arises
  - Tasks: fork(), exec(), setuid(), setgid()
  - Sockets (for connection control): listen()
- Manual classification overrides CE, if latter present, until automatic classification explicitly reenabled
  - re-enablement by writing object id to /rcfs/ce/reclassify

Classification Engines

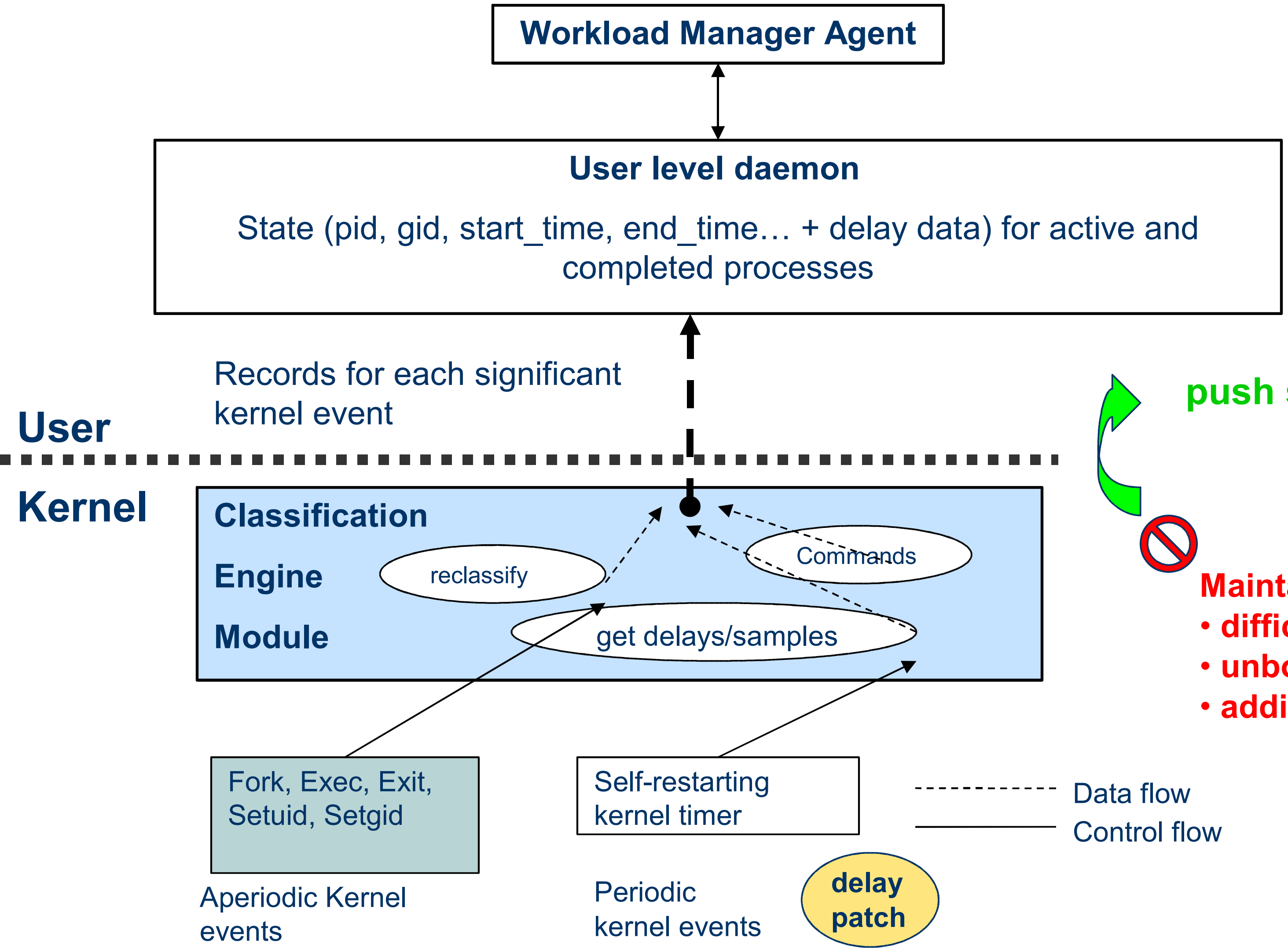
- Optional module for CKRM operation
- Can be custom-built outside CKRM project
  - Only needs to adhere to CKRM's "return classification" interface
  - Module's output is a recommendation that may be rejected by CKRM core
- CKRM provides two rule-based classification engines
- RBCE (Rule-Based Classification Engine)
  - Flexible classification using rule matching
  - Expected to meet manual system administration needs
- CRBCE (enhancements to RBCE)
  - Supplies user space with data useful for goal-oriented workload management
  - Expected to meet WLM middleware needs

RBCE

- Classification rule
  - { [(attr,value)]+ -> class }
  - Attributes of task: uid, gid, executable name, application tag
  - Created by echoing terms to /rcfs/ce/rules/<rulename>
- Classification rules ordered
  - Matched in order at classification point by CE module
  - “Catch-all” rule advisable for no-match case
- Application tags
  - Additional flexibility for grouping based on application specific criteria
    - Application informs WLM of transaction start
    - WLM sets application tag
    - Application tag used in classifying application processes



CRBCE and Resource monitoring



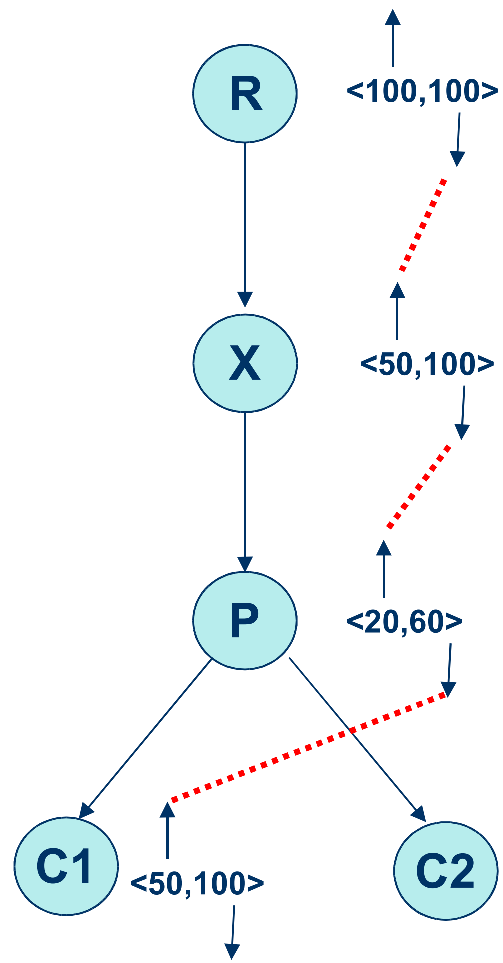
push state to user space

Maintaining state in kernel

- difficult to do ..
- unbound in requirements
- additional complexity

Shares

- Distinguish for each resource
  - limit (upper bound)
  - guarantee (lower bound)
    - No oversubscription, no starvation !
- Parent provides a base (think 100%)
  - max_limit, total_guarantee
- Child gets a relative fraction
  - limit < max_limit(parent)
  - guarantee/total_guarantee(parent)
- Actual Shares received
  - determined by path…
- Changing shares
  - Possible without touching siblings' values



50/60 * 20/100 * 50/100 = 8.3%

echo "res=cpu, guarantee=50, total_guarantee=100" \
> /rcfs/taskclass/R/X/shares

Stats

- cat /path/to/class/stats
- Multiple lines from each active controller
  - Prefer one statistic per line a la vmstat
  - Data, interpretation is controller specific
- Leaf nodes updated accurately
  - Parents updated lazily

Resource Controllers

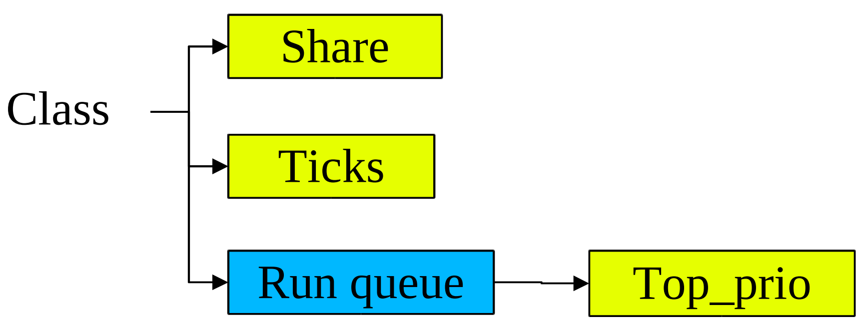
- Each task associated with a class
  - Task resource requests queued by class
  - Explicit or implicit per-class queues
- Control
  - Share based preferential service to class queues
- Monitoring
  - Additionally maintain class statistics
- Network classes
  - Not tied to tasks but ipaddress:port
  - controlled similarly

Resource Controller Status

- Controllers provided
  - CPU
  - Physical Memory (preliminary port available)
  - Disk I/O bandwidth (CFQv2 based port expected 8/04)
  - Inbound Socket Connections
- Virtual resource controller for number of tasks
  - template
  - Prevent fork bombs
- Other controllers can be developed as needed

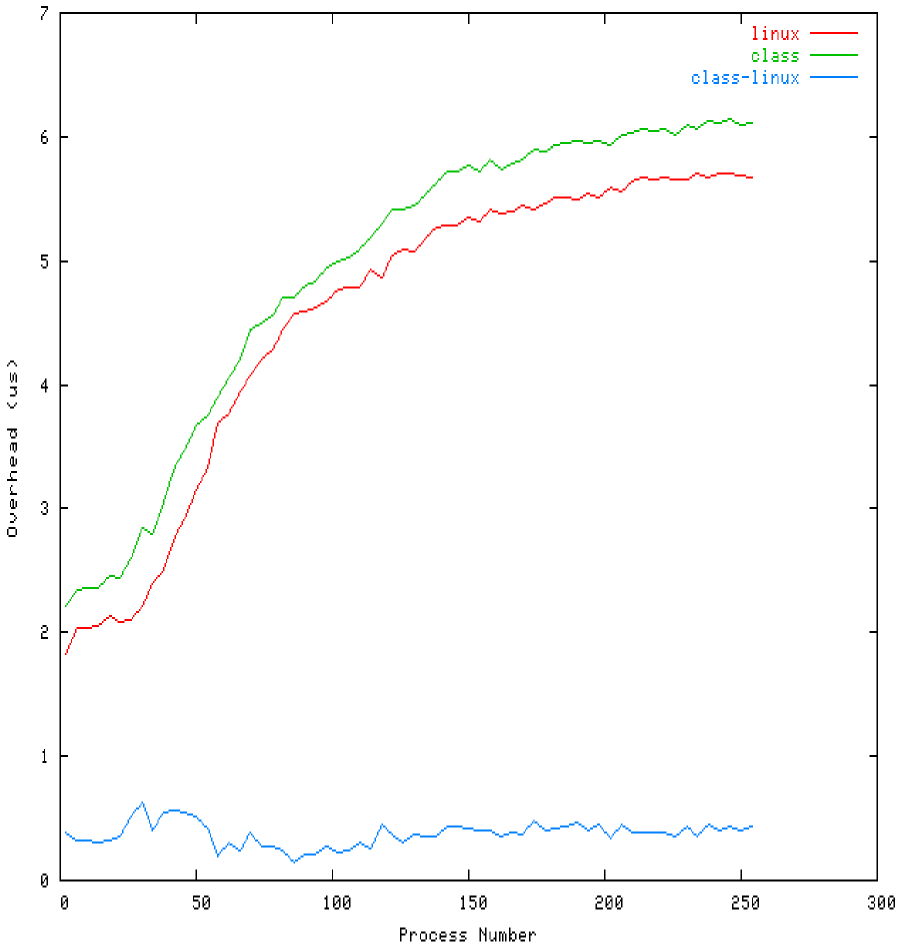
CKRM CPU Scheduler

- 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**

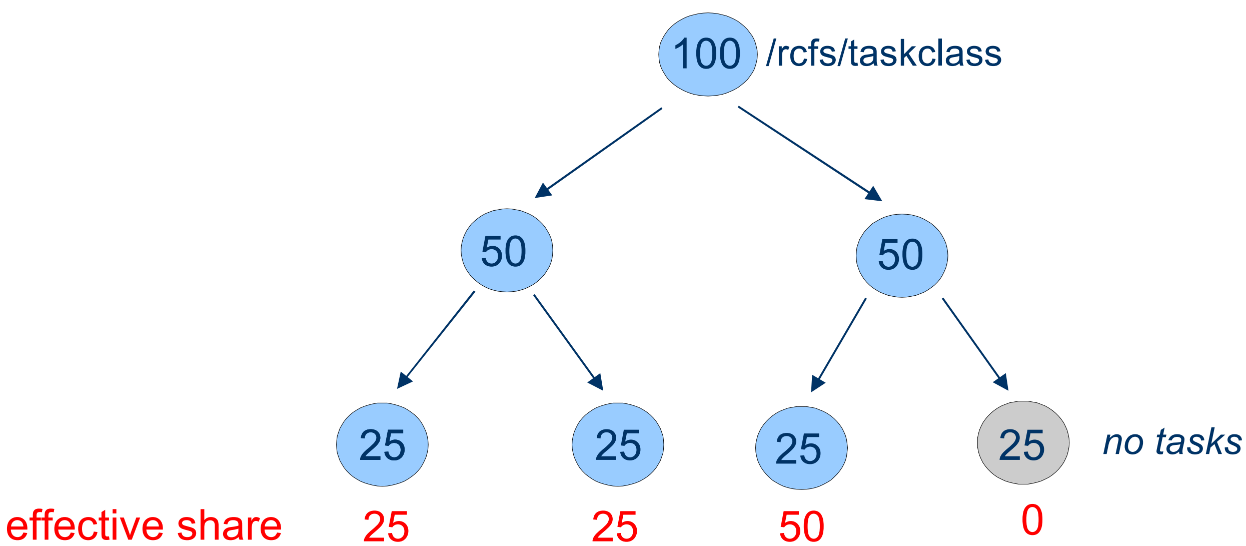
Scheduling Overhead



- 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

Managing hierarchies

- Traversing hierarchies costly
- Lazy monitoring and control
  - Update parent usage
  - Redistribute effective share
  - Kernel thread or user space
  - Reusable for different controllers



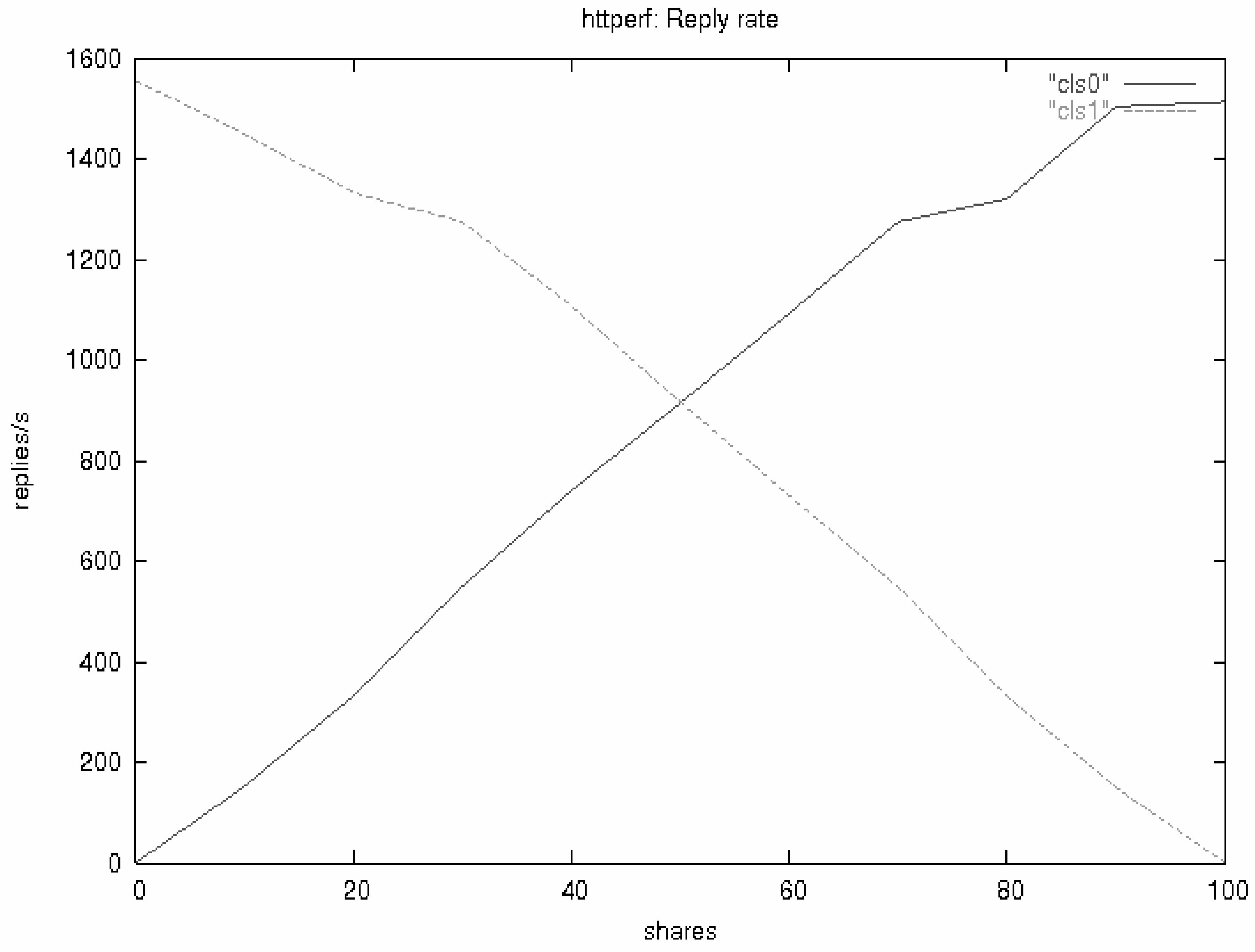
Inbound Connection Control

- Using Accept Queue classes
- Classify using (local, remote) * (IP, port)
  - Iptables rules to MARK SYN packets
- Split single accept queue into multiple queues
  - Assign shares to classes/queues
  - Use weighted round robin to accept packets
- Inbound connections accepted in proportion to shares assigned
  - Response time proportionally reduced
- Drawbacks
  - Classification hard in presence of proxies and multiple classes on same remote host

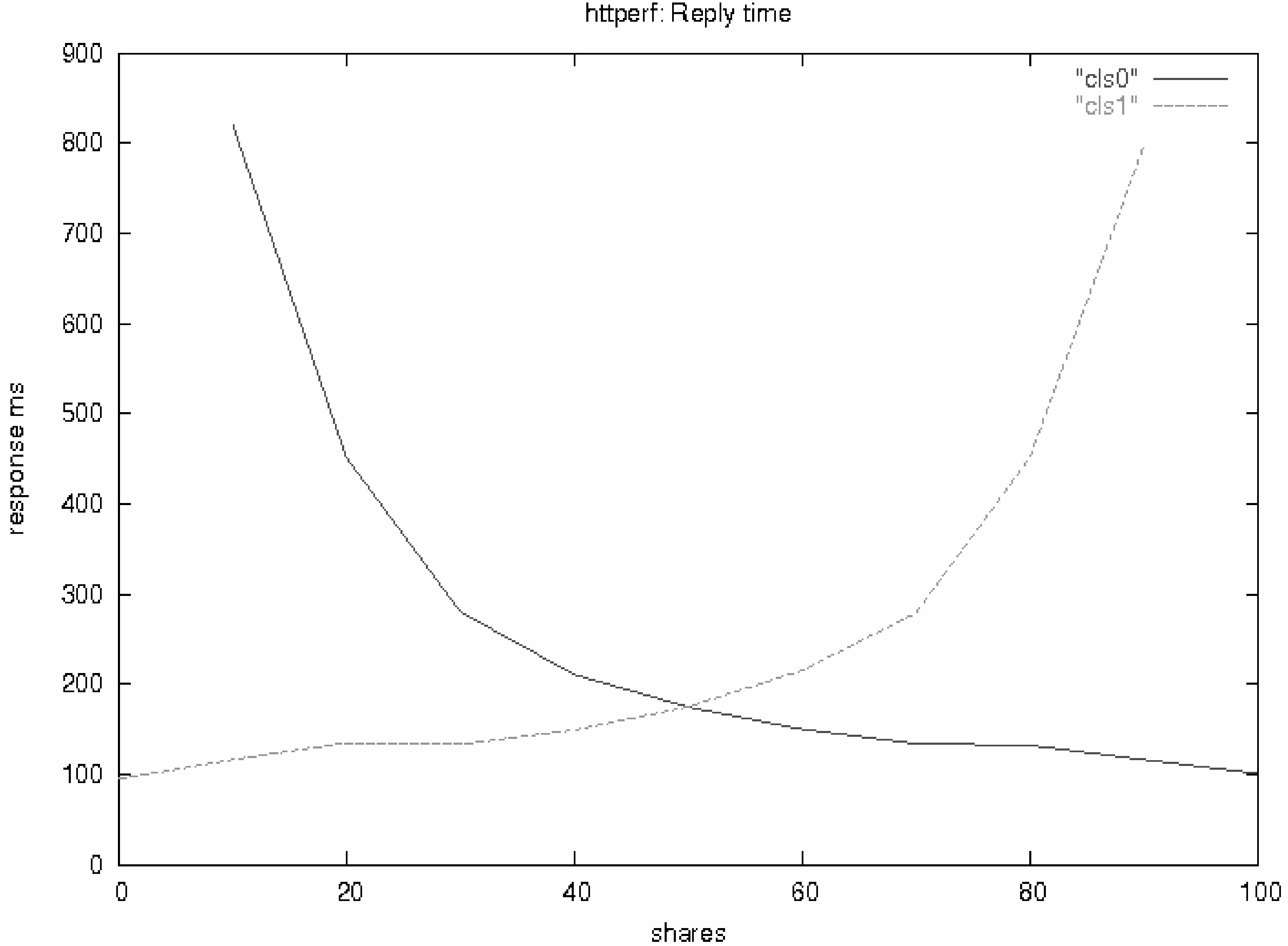
AcceptQ Experimental Setup

- Server
  - Httpd (apache) webserver with default config
  - ckrm with 'ckrm_listenaq' controller
- Two clientsrunning httperf
- Use iptables on the server to assign MARK values to connection requests from the client machines. The MARK values are assigned based on the client machines' IP addresses
- httperf run multiple times on each client against the server with each run corresponding to a different share setting for the clients.
  - default class = 90, class 1 = 10
  - default class = 40, class 1 = 60

AcceptQ: Reply Rate



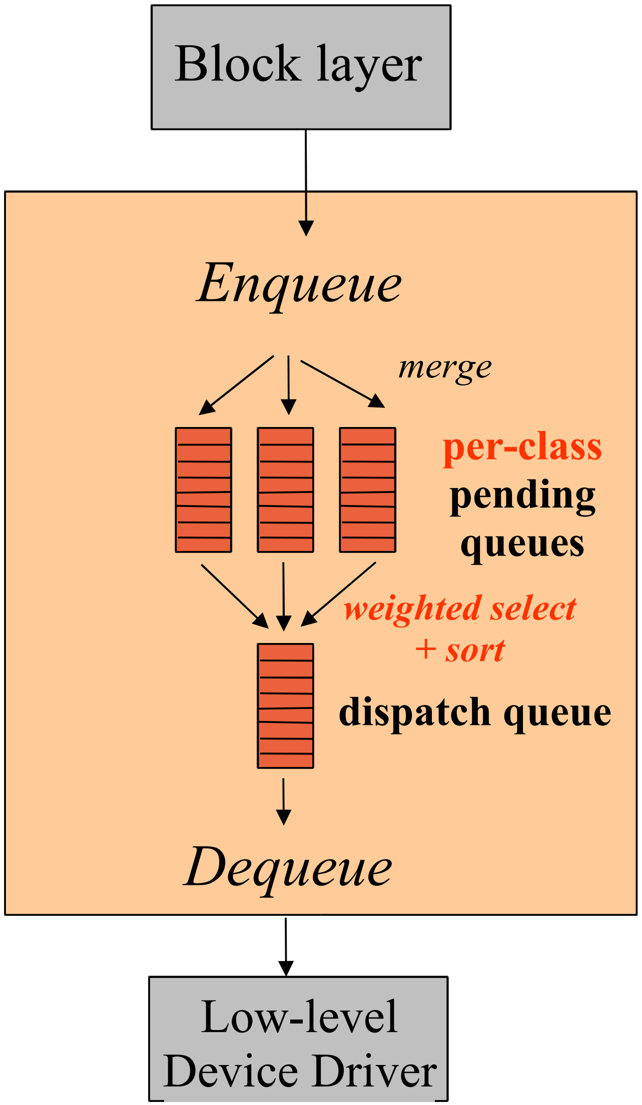
AcceptQ: Response Time



CKRM Memory Control

- 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
- Experimenting with alternate schemes

CKRM I/O Scheduler



- CFQ v2 variant
  - Kernel enforcement of non-hierarchical shares
  - User-level, lazy enforcement of hierarchical shares
- Future experimental work
  - Add anticipation
    - Wait and service next request from same task until class share exceeds high-water mark
  - Add deadlines
    - Sort/fifo lists for each class

Future Work

- Complete port of remaining schedulers to RCFS API
  - PlanetLab vserver + CKRM prototype
- Testing, optimization of hierarchical control
- Investigate suggestions from Kernel Summit'04
  - Separate per-controller classes
    - Visible to user ?
  - Reuse kernel data structures like struct user ?
- Explore merger of monitoring with related projects
  - ELSA/CSA

Class-based Kernel Resource Management

http://ckrm.sf.net

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