CS194-24
Advanced Operating Systems Structures and Implementation
Lecture 18

Dominant Resource Fairness
Two-Level Scheduling

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Goals for Today

- DRF
- Lithe
- Two-Level Scheduling/Tessellation

Interactive is important!

Ask Questions!

Note: Some slides and/or pictures in the following are adapted from slides ©2013

Recall: CFS (Continued)

- Idea: track amount of "virtual time" received by each process when it is executing
  - Take real execution time, scale by weighting factor
    - » Lower priority ⇒ real time divided by smaller weight
  - Keep virtual time advancing at same rate among processes. Thus, scaling factor adjusts amount of CPU time/process
- More details
  - Weights relative to Nice-value 0
    - » Relative weights~: $(1.25)^{-nice}$
    - » vruntime = runtime/relative_weight
  - Processes with nice-value 0 ⇒
    - » vruntime advances at same rate as real time
  - Processes with higher nice value (lower priority) ⇒
    - » vruntime advances at faster rate than real time
  - Processes with lower nice value (higher priority) ⇒
    - » vruntime advances at slower rate than real time

Recall: EDF: Schedulability Test

Theorem (Utilization-based Schedulability Test):

A task set $T_1, T_2, \ldots, T_n$ with $D_i = P_i$ is schedulable by the earliest deadline first (EDF) scheduling algorithm if

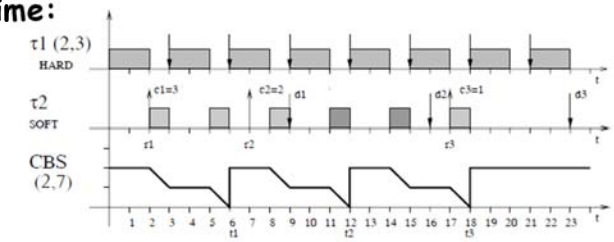
$$\sum_{i=1}^{n} \left(\frac{C_i}{D_i} \right) \leq 1$$

Exact schedulability test (necessary + sufficient)

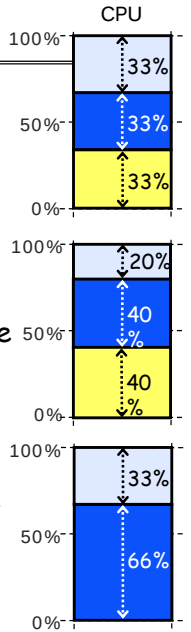
Proof: [Liu and Layland, 1973]

Recall: Constant Bandwidth Server

- Intuition: give fixed share of CPU to certain of jobs
  - Good for tasks with probabilistic resource requirements
- Basic approach: Slots (called "servers") scheduled with EDF, rather than jobs
  - CBS Server defined by two parameters: Q_s and T_s
  - Mechanism for tracking processor usage so that no more than Q_s CPU seconds used every T_s seconds when there is demand. Otherwise get to use processor as you like
- Since using EDF, can mix hard-realtime and soft realtime:



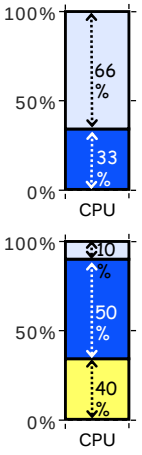
What is Fair Sharing?



- n users want to share a resource (e.g., CPU)
  - Solution:
    Allocate each 1/n of the shared resource
- *Generalized by max-min fairness*
  - Handles if a user wants less than its fair share
  - E.g. user 1 wants no more than 20%
- Generalized by *weighted max-min fairness*
  - Give weights to users according to importance
  - User 1 gets weight 1, user 2 weight 2

Why is Fair Sharing Useful?

- *Weighted Fair Sharing / Proportional Shares*
  - User 1 gets weight 2, user 2 weight 1
- *Priorities*
  - Give user 1 weight 1000, user 2 weight 1
- *Revervations*
  - Ensure user 1 gets 10% of a resource
  - Give user 1 weight 10, sum weights ≤ 100
- *Isolation Policy*
  - Users cannot affect others beyond their fair share



Properties of Max-Min Fairness

- Share guarantee
  - Each user can get at least 1/n of the resource
  - But will get less if her demand is less
- Strategy-proof
  - Users are not better off by asking for more than they need
  - Users have no reason to lie
- Max-min fairness is the only "reasonable" mechanism with these two properties

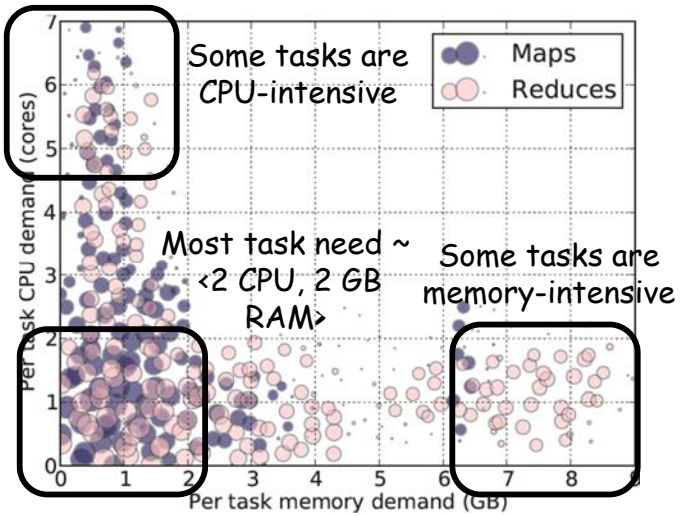
Why Care about Fairness?

- Desirable properties of max-min fairness
  - *Isolation policy:*
    A user gets her fair share irrespective of the demands of other users
  - *Flexibility separates mechanism from policy:*
    Proportional sharing, priority, reservation,...
- *Many schedulers* use max-min fairness
  - Datacenters: Hadoop's fair sched, capacity, Quincy
  - OS: rr, prop sharing, lottery, linux cfs, ...
  - Networking: wfq, wf2q, sfq, drr, csfq, ...

When is Max-Min Fairness not Enough?

- Need to schedule *multiple, heterogeneous* resources
  - Example: Task scheduling in datacenters
    - » Tasks consume more than just CPU – CPU, memory, disk, and I/O
- What are today's datacenter task demands?

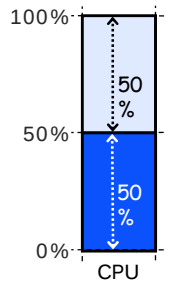
Heterogeneous Resource Demands



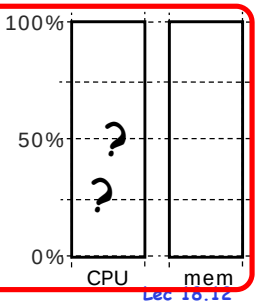
2000-node Hadoop Cluster at Facebook (Oct 2010)

Problem

Single resource example
- 1 resource: CPU
- User 1 wants <1 CPU> per task
- User 2 wants <3 CPU> per task



Multi-resource example
- 2 resources: CPUs & memory
- User 1 wants <1 CPU, 4 GB> per task
- User 2 wants <3 CPU, 1 GB> per task
- *What is a fair allocation?*



Problem definition

How to fairly share multiple resources when users have heterogeneous demands on them?

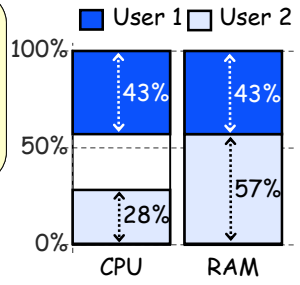
Model

- Users have *tasks* according to a *demand vector*
  - e.g. <2, 3, 1> user's tasks need 2 R_1, 3 R_2, 1 R_3
  - Not needed in practice, can simply measure actual consumption
- Resources given in multiples of demand vectors
- Assume divisible resources

A Natural Policy: Asset Fairness

- *Asset Fairness*
  - Equalize each user's *sum of resource shares*

Problem
User 1 has < 50% of both CPUs and RAM
Better off in a separate cluster with 50% of the resources



- Asset fairness yields
  - U_1: 15 tasks: 30 CPUs, 30 GB (Σ=60)
  - U_2: 20 tasks: 20 CPUs, 40 GB (Σ=60)

Share Guarantee

- Every user should get $1/n$ of at least one resource
- Intuition:
  - "You shouldn't be worse off than if you ran your own cluster with $1/n$ of the resources"

Desirable Fair Sharing Properties

- Many desirable properties
  - Share Guarantee
  - Strategy proofness
  - Envy-freeness
  - Pareto efficiency
  - Single-resource fairness
  - Bottleneck fairness
  - Population monotonicity
  - Resource monotonicity

DRF focuses on these properties

Cheating the Scheduler

- Some users will *game* the system to get more resources
- Real-life examples
  - A cloud provider had quotas on map and reduce slots
    Some users found out that the map-quota was low
    - » Users implemented maps in the reduce slots!
  - A search company provided dedicated machines to users that could ensure certain level of utilization (e.g. 80%)
    - » Users used busy-loops to inflate utilization

Two Important Properties

- Strategy-proofness
  - A user should not be able to increase her allocation by lying about her demand vector
  - Intuition:
    - » Users are incentivized to make truthful resource requirements
- Envy-freeness
  - No user would ever strictly prefer another user's lot in an allocation
  - Intuition:
    - » Don't want to trade places with any other user

Challenge

- A fair sharing policy that provides
  - Strategy-proofness
  - Share guarantee
- Max-min fairness for a single resource had these properties
  - Generalize max-min fairness to multiple resources

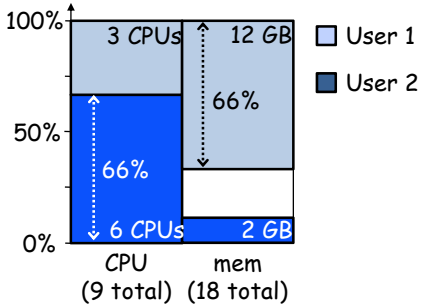
Dominant Resource Fairness

- A user's *dominant resource* is the resource she has the biggest share of
  - Example:
    Total resources: <10 CPU, 4 GB>
    User 1's allocation: <2 CPU, 1 GB>
    Dominant resource is memory as 1/4 > 2/10 (1/5)

- A user's *dominant share* is the fraction of the dominant resource she is allocated
  - User 1's dominant share is 25% (1/4)

Dominant Resource Fairness (2)

- *Apply max-min fairness to dominant shares*
- Equalize the dominant share of the users
  - Example:
    Total resources: <9 CPU, 18 GB>
    User 1 demand: <1 CPU, 4 GB> dominant res: mem
    User 2 demand: <3 CPU, 1 GB> dominant res: CPU



DRF is Fair

- DRF is strategy-proof
- DRF satisfies the share guarantee
- DRF allocations are envy-free

See DRF paper for proofs

Online DRF Scheduler

Whenever there are available resources and tasks to run:
Schedule a task to the user with smallest dominant share

- O(log *n*) time per decision using binary heaps
- Need to determine demand vectors

Alternative: Use an Economic Model

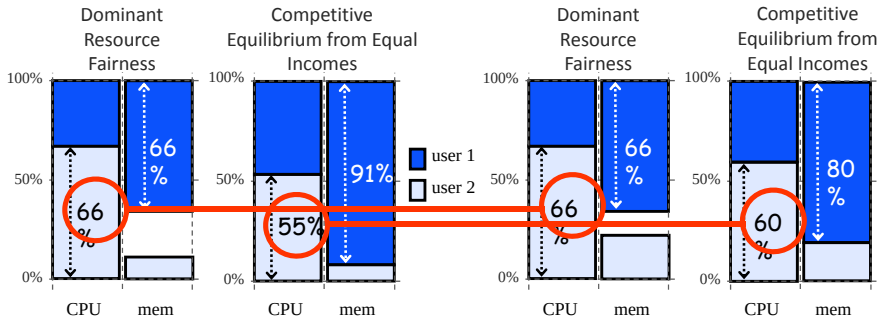
- Approach
  - Set prices for each good
  - Let users buy what they want
- How do we determine the right prices for different goods?
- Let the market determine the prices
- *Competitive Equilibrium from Equal Incomes (CEEI)*
  - Give each user 1/n of every resource
  - Let users trade in a perfectly competitive market
- Not strategy-proof!

Determining Demand Vectors

- They can be *measured*
  - Look at actual resource consumption of a user
- They can be *provided* the by user
  - What is done today
- In both cases, strategy-proofness incentivizes user to consume resources wisely

DRF vs CEEI

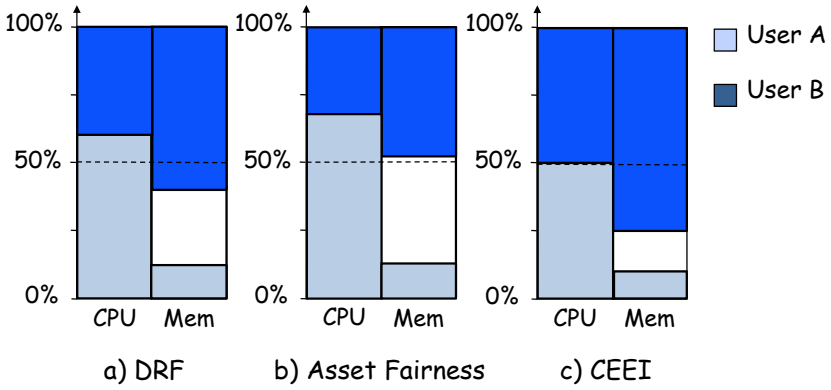
- User 1: <1 CPU, 4 GB> User 2: <3 CPU, 1 GB>
  - DRF more fair, CEEI better utilization



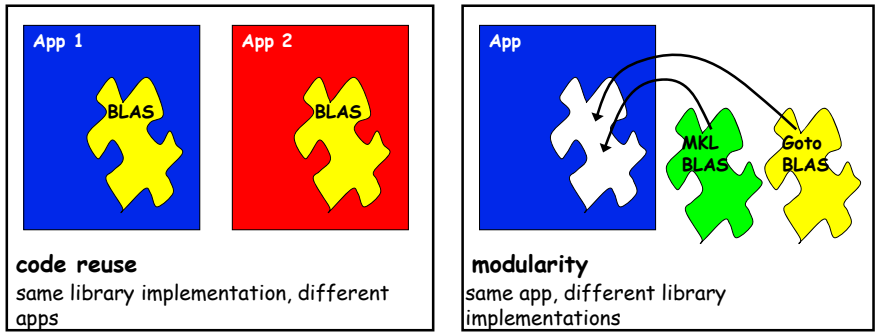
- User 1: <1 CPU, 4 GB> User 2: <3 CPU, 2 GB>
  - User 2 increased her share of both CPU and memory

Example of DRF vs Asset vs CEEI

- Resources <1000 CPUs, 1000 GB>
- 2 users A: <2 CPU, 3 GB> and B: <5 CPU, 1 GB>



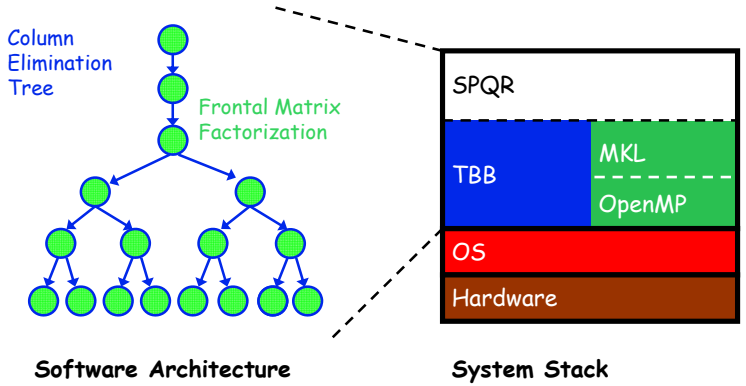
Composability is Essential



Composability is key to building large, complex apps.

Motivational Example

Sparse QR Factorization
(Tim Davis, Univ of Florida)



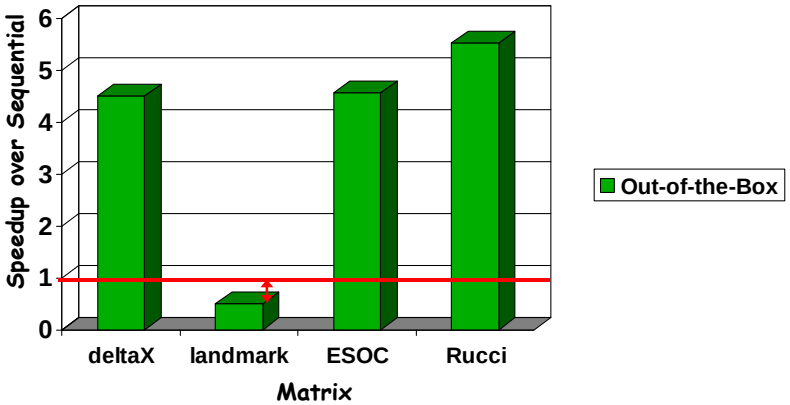
Software Architecture **System Stack**

TBB, MKL, OpenMP

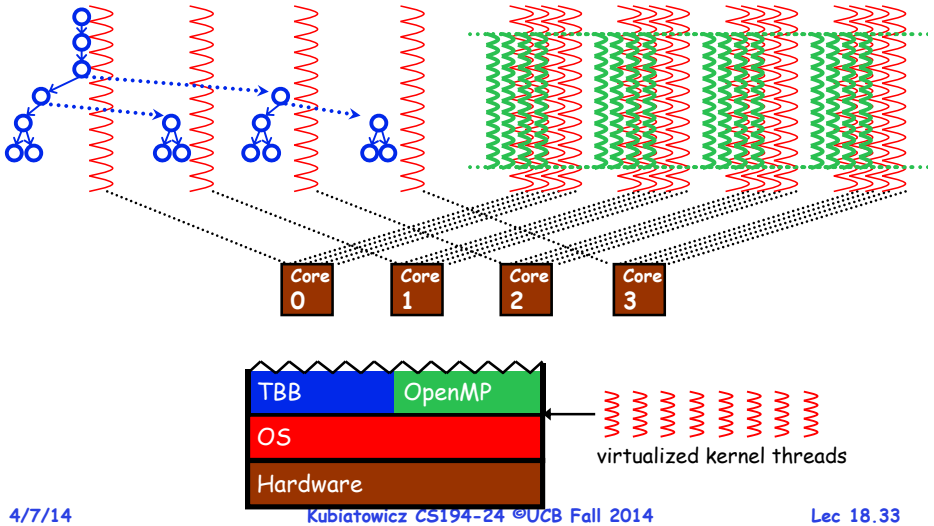
- Intel's Threading Building Blocks (TBB)
  - Library that allows programmers to express parallelism using a higher-level, task-based, abstraction
  - Uses work-stealing internally (i.e. Cilk)
  - Open-source
- Intel's Math Kernel Library (MKL)
  - Uses OpenMP for parallelism
- OpenMP
  - Allows programmers to express parallelism in the SPMD-style using a combination of compiler directives and a runtime library
  - Creates SPMD teams internally (i.e. UPC)
  - Open-source implementation of OpenMP from GNU (libgomp)

Suboptimal Performance

Performance of SPQR on 16-core AMD Opteron System



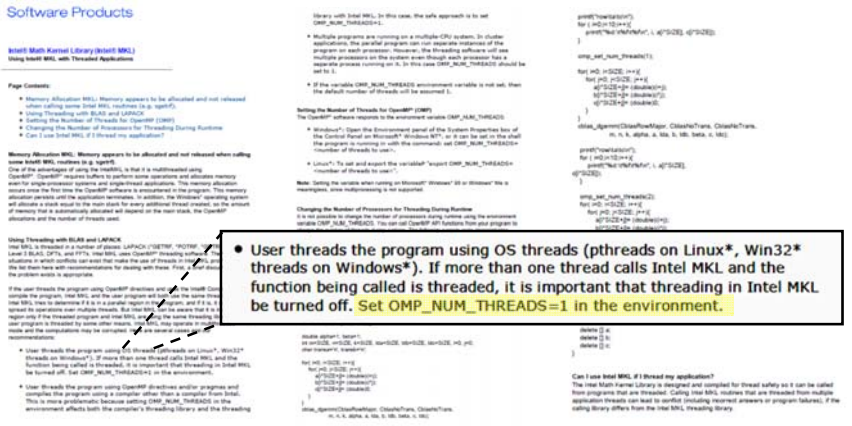
Out-of-the-Box Configurations



Providing Performance Isolation

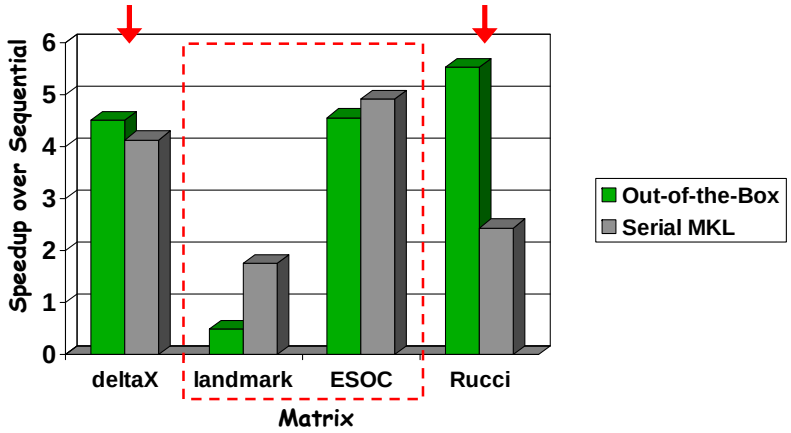
Using Intel MKL with Threaded Applications

http://www.intel.com/support/performancetools/libraries/mkl/sb/CS-017177.htm

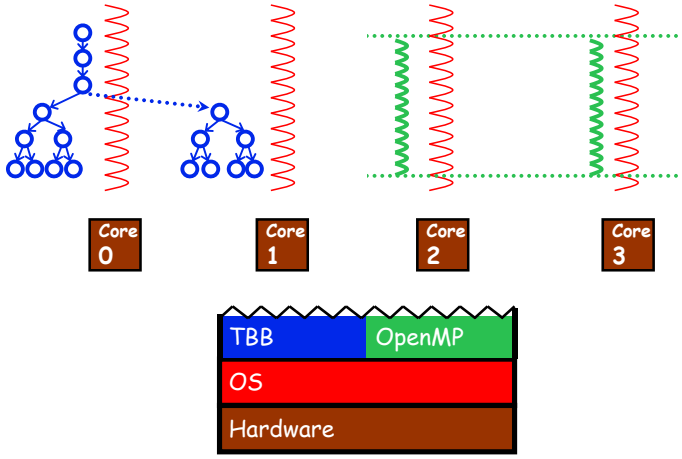


"Tuning" the Code

Performance of SPQR on 16-core AMD Opteron System



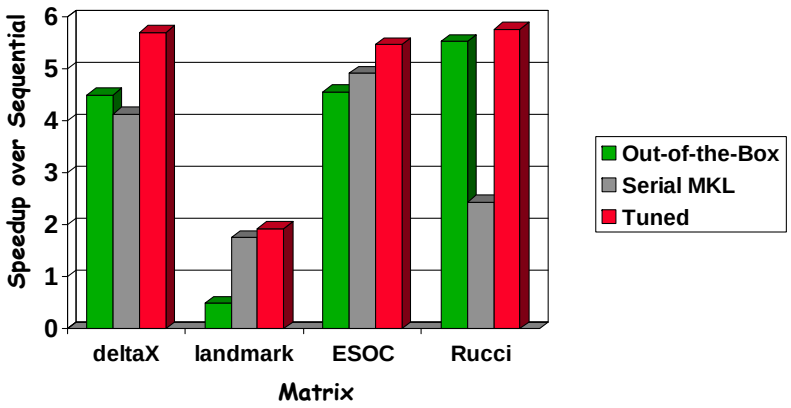
Partition Resources



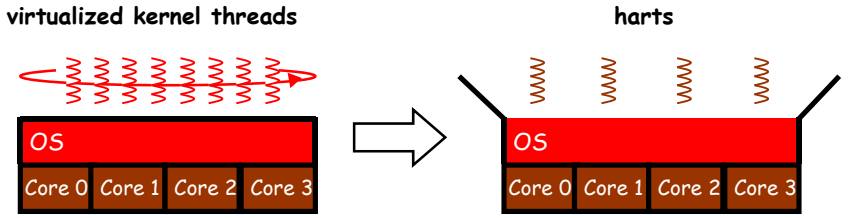
Tim Davis' "tuned" SPQR by manually partitioning the resources.

"Tuning" the Code (continued)

Performance of SPQR on 16-core AMD Opteron System

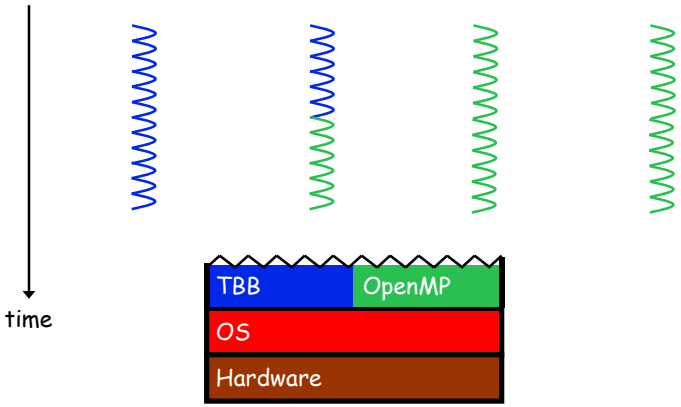


Harts: Hardware Threads

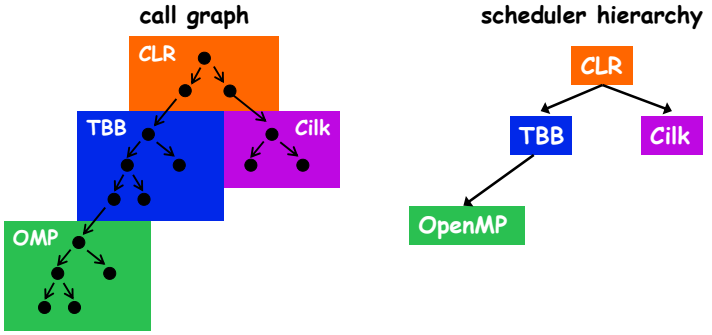


- Expose true hardware resources
  - Applications requests harts from OS
  - Application "schedules" the harts itself (two-level scheduling)
  - Can both space-multiplex and time-multiplex harts … but never time-multiplex harts of the same application

Sharing Harts (Dynamically)

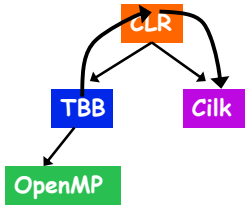


How to Share Harts?

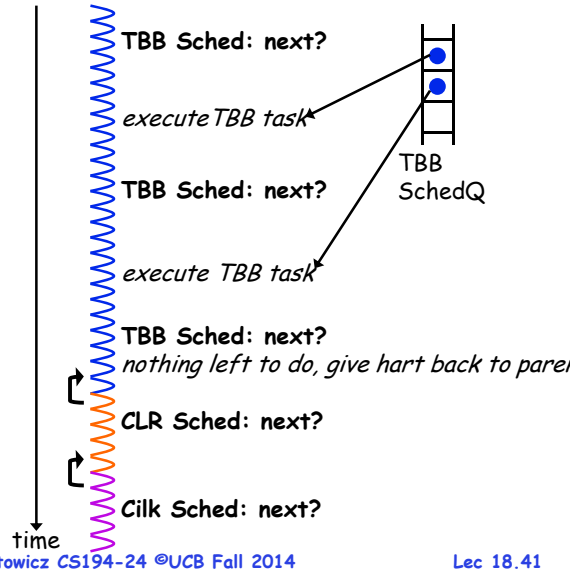


- **Hierarchically:** Caller gives resources to callee to execute
- **Cooperatively:** Callee gives resources back to caller when done

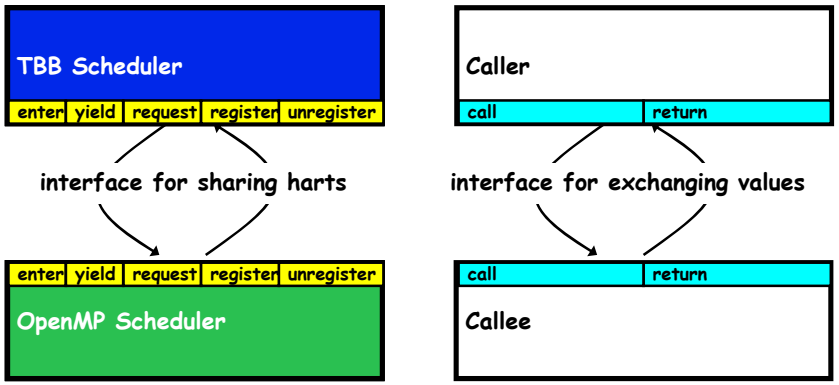
A Day in the Life of a Hart



- Non-preemptive scheduling.

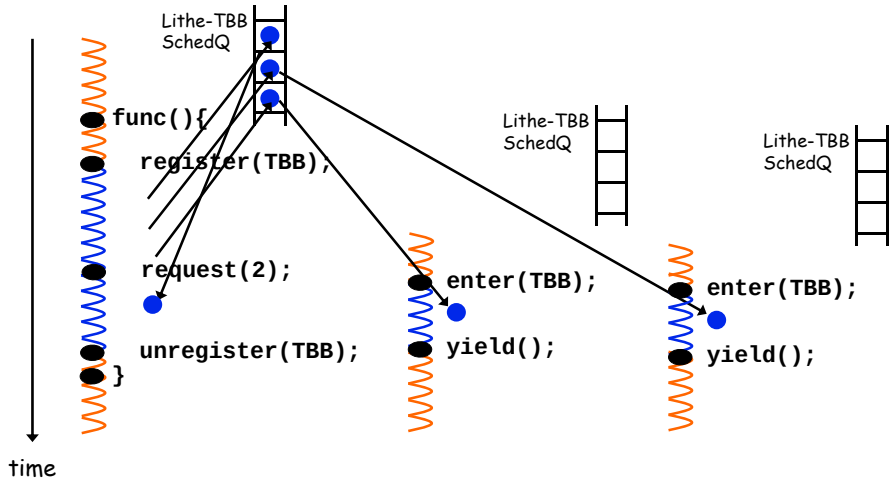


Lithe (ABI)

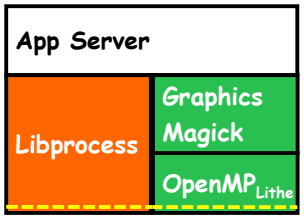


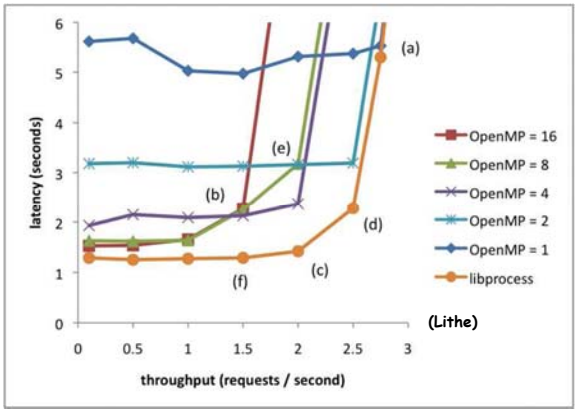
- Analogous to function call ABI for enabling interoperable codes.

Putting It All Together



Flickr-Like App Server

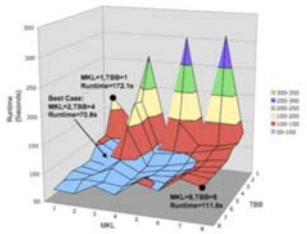




Tradeoff between throughput saturation point and latency.

Case Study: Sparse QR Factorization

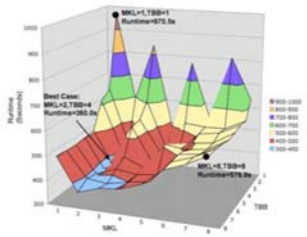
ESOC



Tuned:	70.8
Out-of-the-box:	111.8
Sequential:	172.1

Lithe: 66.7

Rucci

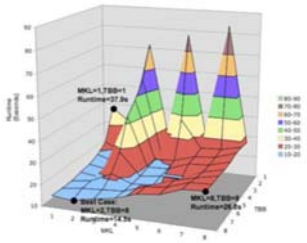


Tuned:	360.0
Out-of-the-box:	576.9
Sequential:	970.5

Lithe: 354.7

Case Study: Sparse QR Factorization

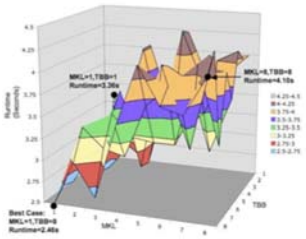
deltaX



Tuned:	14.5
Out-of-the-box:	26.8
Sequential:	37.9

Lithe: 13.6

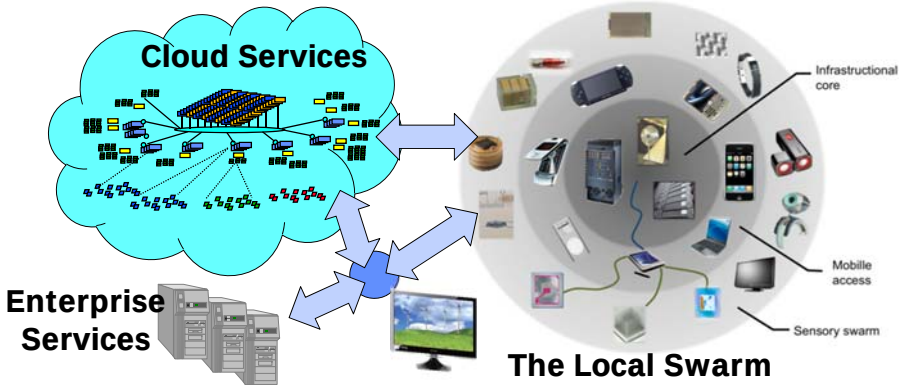
landmark



Tuned:	2.5
Out-of-the-box:	4.1
Sequential:	3.4

Lithe: 2.3

The Swarm of Resources

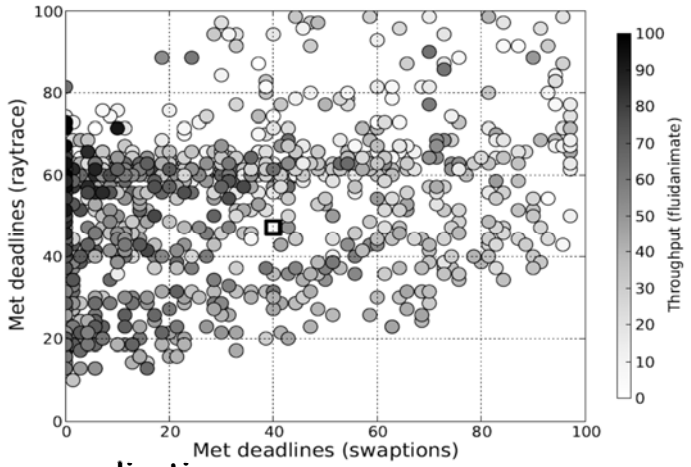


- What system structure required to support Swarm?
  - Discover and Manage resource
  - Integrate sensors, portable devices, cloud components
  - Guarantee responsiveness, real-time behavior, throughput
  - Self-adapting to adjust for failure and performance predictability
  - Uniformly secure, durable, available data

Support for Applications

- Clearly, new Swarm applications will contain:
  - Direct interaction with Swarm and Cloud services
    - » Potentially extensive use of remote services
    - » Serious security/data vulnerability concerns
  - Real Time requirements
    - » Sophisticated multimedia interactions
    - » Control of/interaction with health-related devices
  - Responsiveness Requirements
    - » Provide a good interactive experience to users
  - Explicitly parallel components
    - » However, parallelism may be "hard won" (not embarrassingly parallel)
    - » Must not interfere with this parallelism
- What support do we need for new Swarm applications?
  - No existing OS handles all of the above patterns well!
    - » A lot of functionality, hard to experiment with, possibly fragile, …
    - » Monolithic resource allocation, scheduling, memory management…
  - Need focus on resources, asynchrony, composability

Resource Allocation must be Adaptive



- Three applications:
  - 2 Real Time apps (RayTrace, Swaptions)
  - 1 High-throughput App (Fluidanimate)

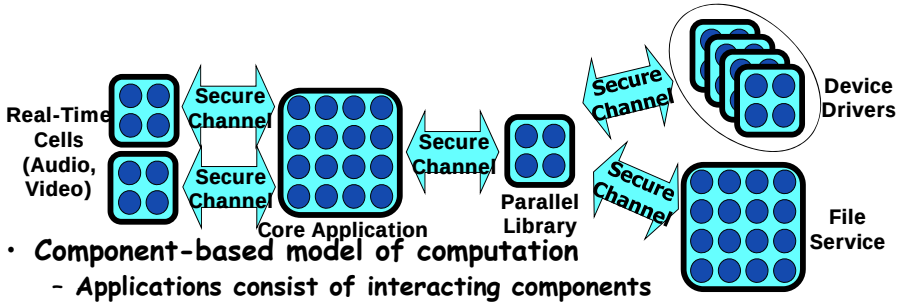
Guaranteeing Resources

- Guaranteed Resources ⇒ Stable software components
  - Good overall behavior
- What might we want to guarantee?
  - Physical memory pages
  - BW (say data committed to Cloud Storage)
  - Requests/Unit time (DB service)
  - Latency to Response (Deadline scheduling)
  - Total energy/battery power available to Cell
- What does it mean to have guaranteed resources?
  - Firm Guarantee (with high confidence, maximum deviation, etc)
  - A Service Level Agreement (SLA)?
  - Something else?
- "Impedance-mismatch" problem
  - The SLA guarantees properties that programmer/user wants
  - The *resources* required to satisfy SLA are not things that programmer/user really understands

New Abstraction: the Cell

- Properties of a Cell
  - A user-level software component with guaranteed resources
  - Has full control over resources it owns ("Bare Metal")
  - Contains at least one memory protection domain (possibly more)
  - Contains a set of secured channel endpoints to other Cells
  - Hardware-enforced security context to protect the privacy of information and decrypt information (a Hardware TCB)
- Each Cell schedules its resources exclusively with application-specific user-level schedulers
  - Gang-scheduled hardware thread resources ("Harts")
  - Virtual Memory mapping and paging
  - Storage and Communication resources
    - » Cache partitions, memory bandwidth, power
  - Use of Guaranteed fractions of system services
- Predictability of Behavior ⇒
  - Ability to model performance vs resources
  - Ability for user-level schedulers to better provide QoS

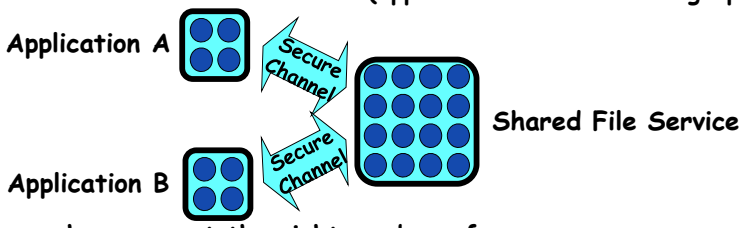
Applications are Interconnected Graphs of Services



- Component-based model of computation
  - Applications consist of interacting components
  - Explicitly asynchronous/non-blocking
  - Components may be local or remote
- Communication defines Security Model
  - Channels are points at which data may be compromised
  - Channels define points for QoS constraints
- Naming (Brokering) process for initiating endpoints
  - Need to find compatible remote services
  - Continuous adaptation: links changing over time!

Impact on the Programmer

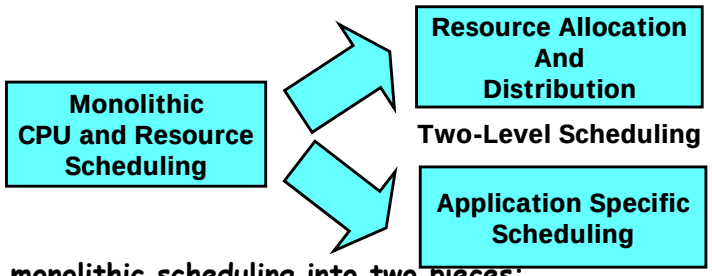
- Connected graph of Cells ⇔ Object-Oriented Programming
  - Lowest-Impact: Wrap a functional interface around channel
    - » Cells hold "Objects", Secure channels carry RPCs for "method calls"
    - » Example: POSIX shim library calling shared service Cells
  - Greater Parallelism: Event triggered programming
- Shared services complicate resource isolation:
  - How to guarantee that each client gets guaranteed fraction of service?
  - Distributed resource attribution (application as distributed graph)



- Must somehow request the right number of resources
  - Analytically? AdHoc Profiling? Over commitment of resources?
  - Clearly doesn't make it easy to adapt to changes in environment

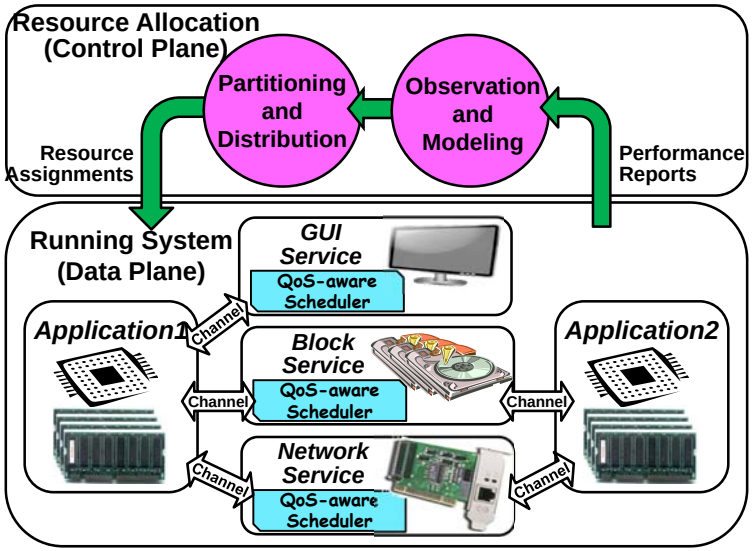
Allocation of Resources
Discovery, Distribution, and Adaptation

Two Level Scheduling: Control vs Data Plane



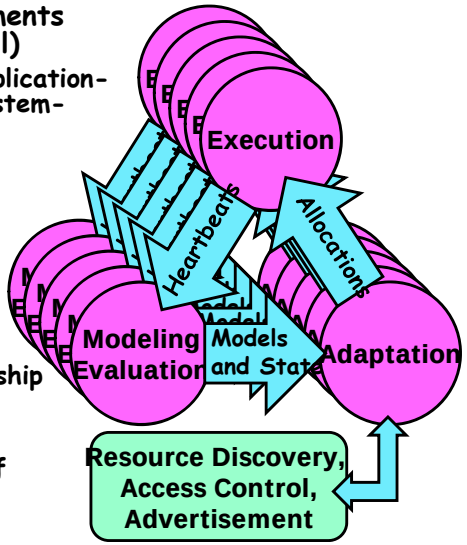
- Split monolithic scheduling into two pieces:
  - Course-Grained Resource Allocation and Distribution to Cells
    - » Chunks of resources (CPUs, Memory Bandwidth, QoS to Services)
    - » Ultimately a hierarchical process negotiated with service providers
  - Fine-Grained (User-Level) Application-Specific Scheduling
    - » Applications allowed to utilize their resources in any way they see fit
    - » Performance Isolation: Other components of the system cannot interfere with Cells use of resources

Adaptive Resource-Centric Computing (ARCC)



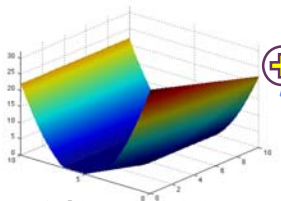
Resource Allocation

- Goal: Meet the QoS requirements of a software component (Cell)
  - Behavior tracked through application-specific "heartbeats" and system-level monitoring
  - Dynamic exploration of performance space to find operation points
- Complications:
  - Many cells with conflicting requirements
  - Finite Resources
  - Hierarchy of resource ownership
  - Context-dependent resource availability
  - Stability, Efficiency, Rate of Convergence, …

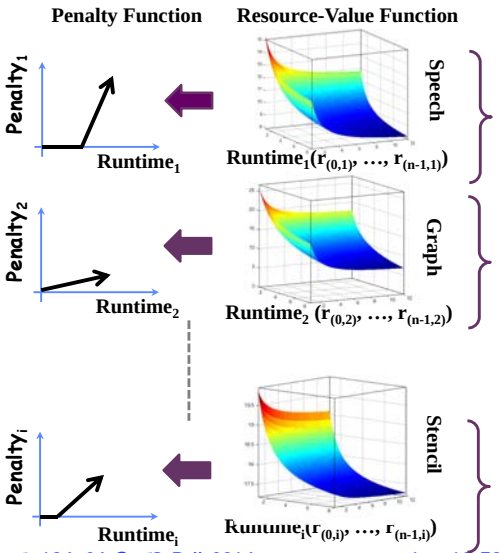


Tackling Multiple Requirements: Express as Convex Optimization Problem

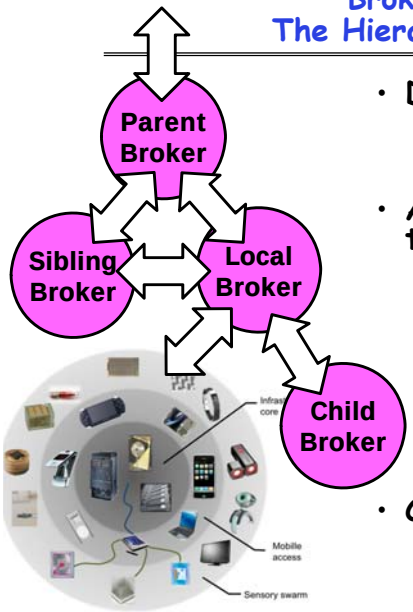
Continuously minimize using the penalty of the system



(subject to restrictions on the total amount of resources)

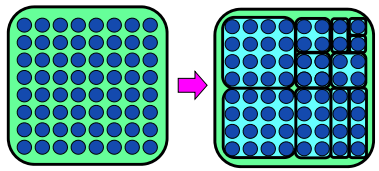


Brokering Service: The Hierarchy of Ownership

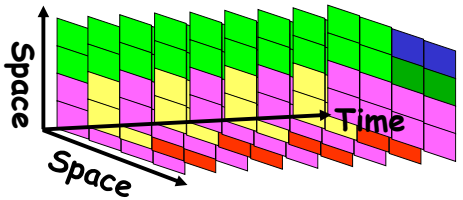


- Discover Resources in "Domain"
  - Devices, Services, Other Brokers
  - Resources self-describing?
- Allocate and Distribute Resources to Cells that need them
  - Solve Impedance-mismatch problem
  - Dynamically optimize execution
  - Hand out Service-Level Agreements (SLAs) to Cells
  - Deny admission to Cells when violates existing agreements
- Complete hierarchy
  - Throughout world graph of applications

Space-Time Partitioning ⇒ Cell



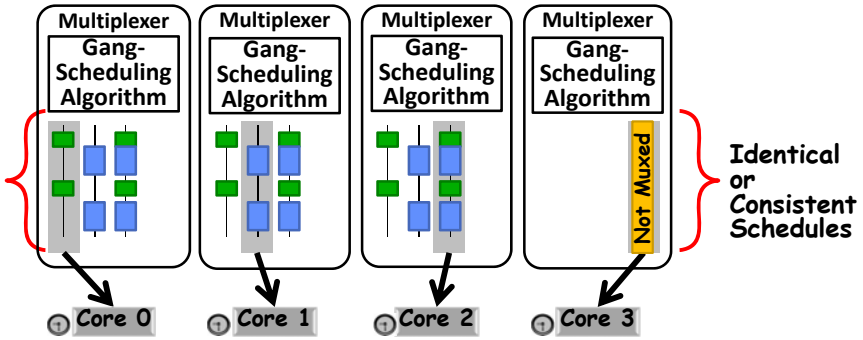
- Spatial Partition: Performance isolation
  - Each partition receives a vector of basic resources
    - » A number HW threads
    - » Chunk of physical memory
    - » A portion of shared cache
    - » A fraction of memory BW
    - » Shared fractions of services



- Partitioning varies over time
  - Fine-grained multiplexing and guarantee of resources
    - » Resources are gang-scheduled
- Controlled multiplexing, not uncontrolled virtualization
- Partitioning adapted to the system's needs

Efficient Space-Time Partitioning

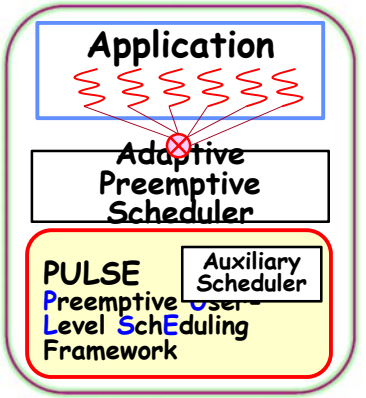
- Communication-Avoiding Gang Scheduling



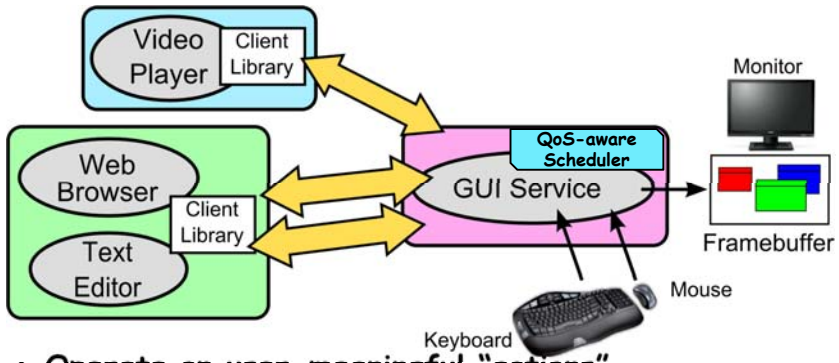
- Supports a variety of Cell types with low overhead
  - Cross between EDF (Earliest Deadline First) and CBS (Constant Bandwidth Server)
  - Multiplexers do not communicate because they use synchronized clocks with sufficiently high precision

Adaptive, Second-Level Preemptive Scheduling Framework

- PULSE: Preemptive User-Level SchEduling Framework for adaptive, premptive schedulers:
  - Dedicated access to processor resources
  - Timer Callback and Event Delivery
  - User-level virtual memory mapping
  - User-level device control
- Auxiliary Scheduler:
  - Interface with policy service
  - Runs outstanding scheduler contexts past synchronization points when resizing happens
  - 2nd-level Schedulers not aware of existence of the Auxiliary Scheduler, but receive resize events
- A number of adaptive schedulers have already been built:
  - Round-Robin, EDF, CBS, Speed Balancing

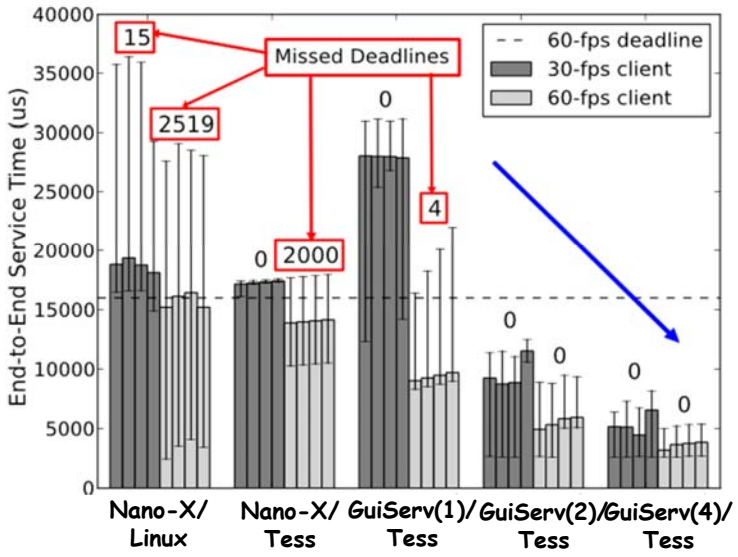


Example: Tesselation GUI Service



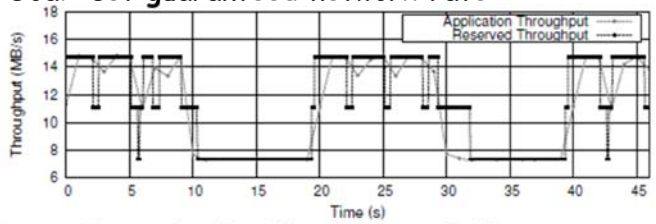
- Operate on user-meaningful "actions"
  - E.g. "draw frame", "move window"
- Service time guarantees (soft real-time)
  - Differentiated service per application
  - E.g. text editor vs video
- Performance isolation from other applications

Composite Resource with Greatly Improved QoS



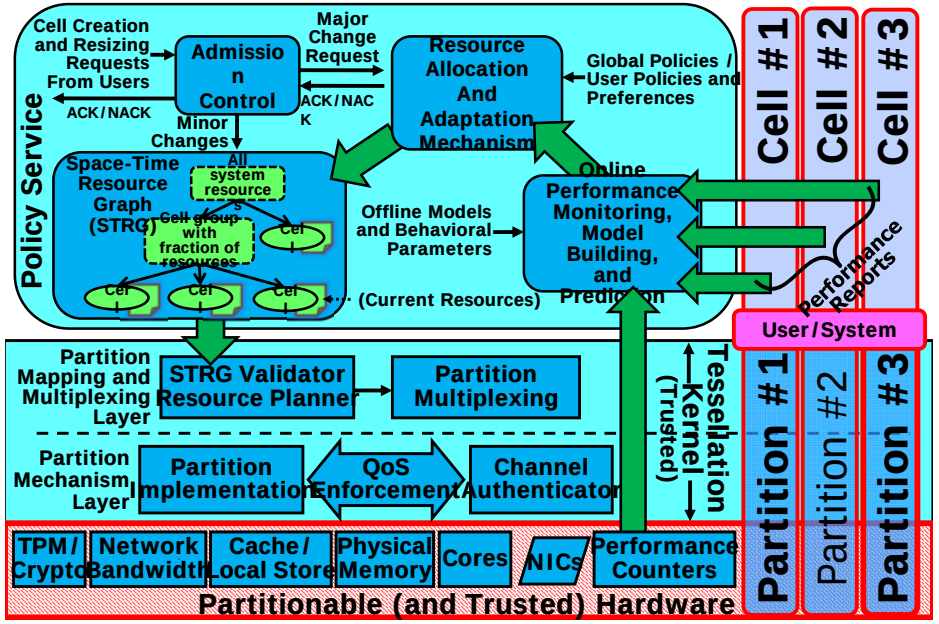
Feedback Driven Policies

- Simple Policies do well but online exploration can cause oscillations in performance
- Example: Video Player interaction with Network
  - Server or GUI changes between high and low bit rate
  - Goal: set guaranteed network rate:



- Alternative: Application Driven Policy
  - Static models
  - Let network choose when to decrease allocation
  - Application-informed metrics such as needed BW

Architecture of Tessellation OS



Summary

- DRF provides multiple-resource fairness in the presence of heterogeneous demand
  - First generalization of max-min fairness to multiple-resources
  - DRF's properties
    - » Share guarantee, at least 1/n of one resource
    - » Strategy-proofness, lying can only hurt you
    - » Performs better than current approaches
- User-Level Scheduling (e.g. Lithe)
  - Adopt scheduling of resources with application knowledge
  - Smooth handoff of processor resources from main application to parallel libraries
- Adaptive Resource-Centric Computing
  - Use of Resources negotiated hierarchically
  - Underlying Execution environment guarantees QoS
  - New Resources constructed from Old ones:
    - » Aggregate resources in combination with QoS-Aware Scheduler
    - » Result is a new resource that can be negotiated for
  - Continual adaptation and optimization