Refactoring the OS around Explicit Resource Containers with Continuous Adaptation

Operating Systems Research in the Par Lab

The OS Group

Par Lab, UC Berkeley

http://tessellation.cs.berkeley.edu

Presented by Juan A. Colmenares, Gage Eads and Sarah Bird

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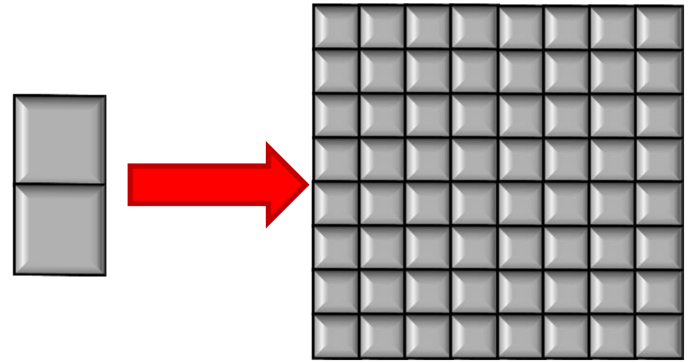
At The Beginning: A.D. 2008

Many-core trend



Mixed workloads on client devices

High throughput
parallel apps

Interactive
apps

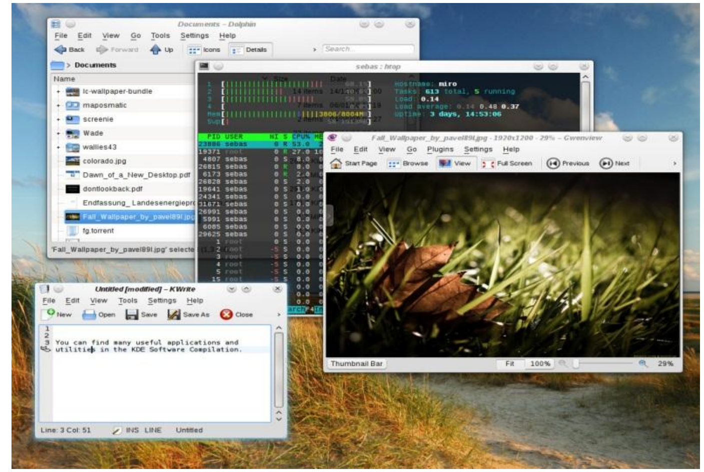
Real-time
apps

Users’ expectations increase with core count

You got more, then

Gimme More!

Common OS Anecdotes



- Screen freezes when running a heavy compile job
- Video chat becomes choppy when a local app starts
- Impossible for me to watch a video with a scientific simulation in the background
- Hey OS, what can I do? Sometimes it goes …

Can We Solve Those Problems? Can We Reinvent the OS to … ?

- Take advantage of many-core platforms
- Properly serve simultaneous applications of different types and with conflicting requirements
- Meet users' expectations about performance

We said: "Yes, we can!"

and started

Tessellation OS, Lithe, and PACORA

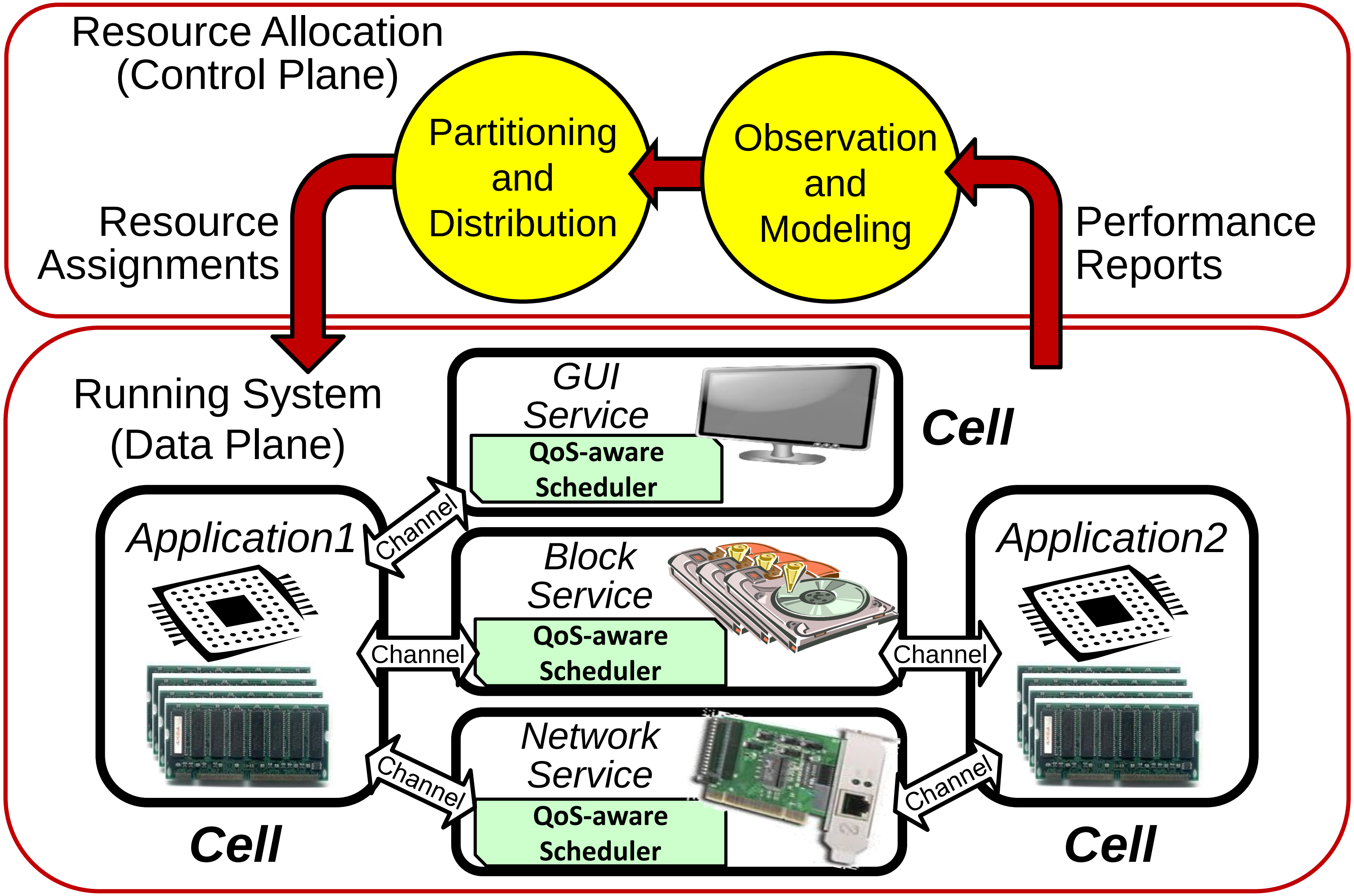
Goals in Tessellation OS

- Support a dynamic mix of high-throughput parallel, interactive, and real-time applications
- Allow applications to deliver guaranteed or at least consistent performance
- Enable adaptation to changes in the application mix and resource availability

Focus on Resources
to Provide Performance Guarantees

- What do we want to guarantee?
  - Throughput (e.g., requests/sec)
  - Latency to response (e.g., service time)
  - Others: energy/power budget
- What type of guarantees?
  - Probabilistic with high confidence
- The “impedance-mismatch” problem
  - Service Level Agreements (SLAs) indicate properties that programmer/user wants
  - The resources required to satisfy the SLA are not things that programmer/user really understands

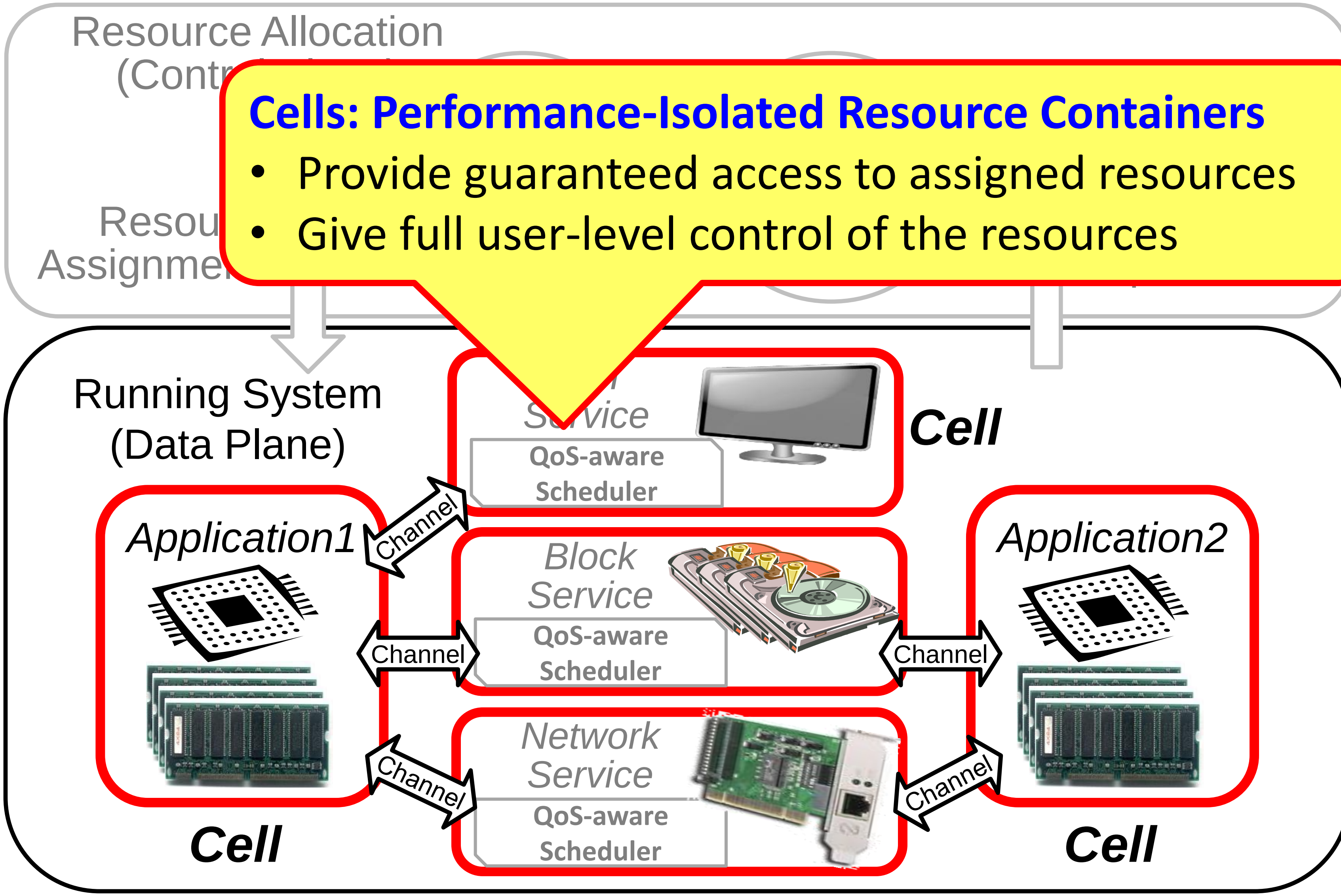
Adaptive Resource-Centric Computing (ARCC) [DAC'13]



Adaptive Resource-Centric Computing (ARCC)

Cells: Performance-Isolated Resource Containers

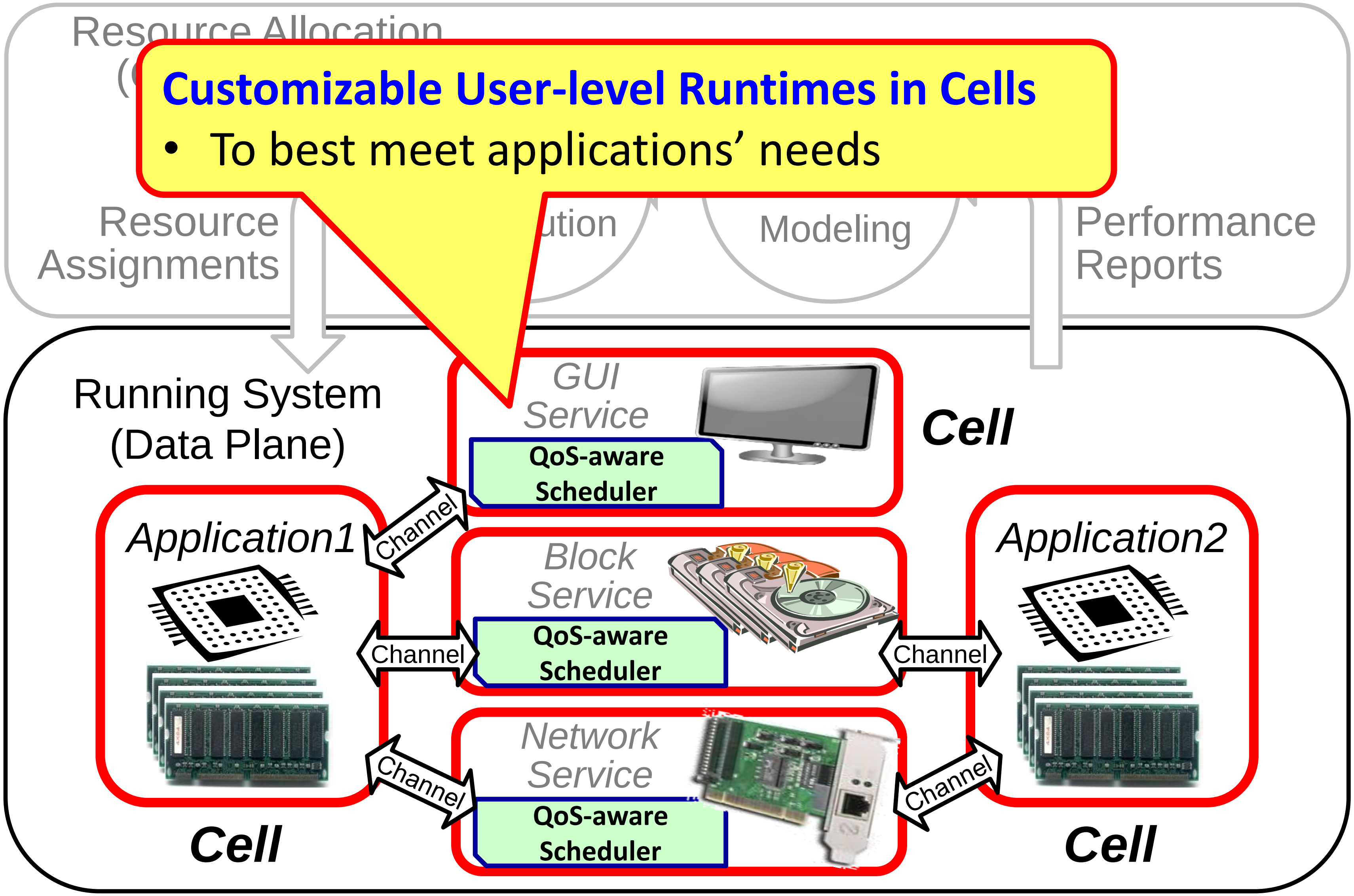
- Provide guaranteed access to assigned resources
- Give full user-level control of the resources



Adaptive Resource-Centric Computing (ARCC)

Customizable User-level Runtimes in Cells

- To best meet applications' needs



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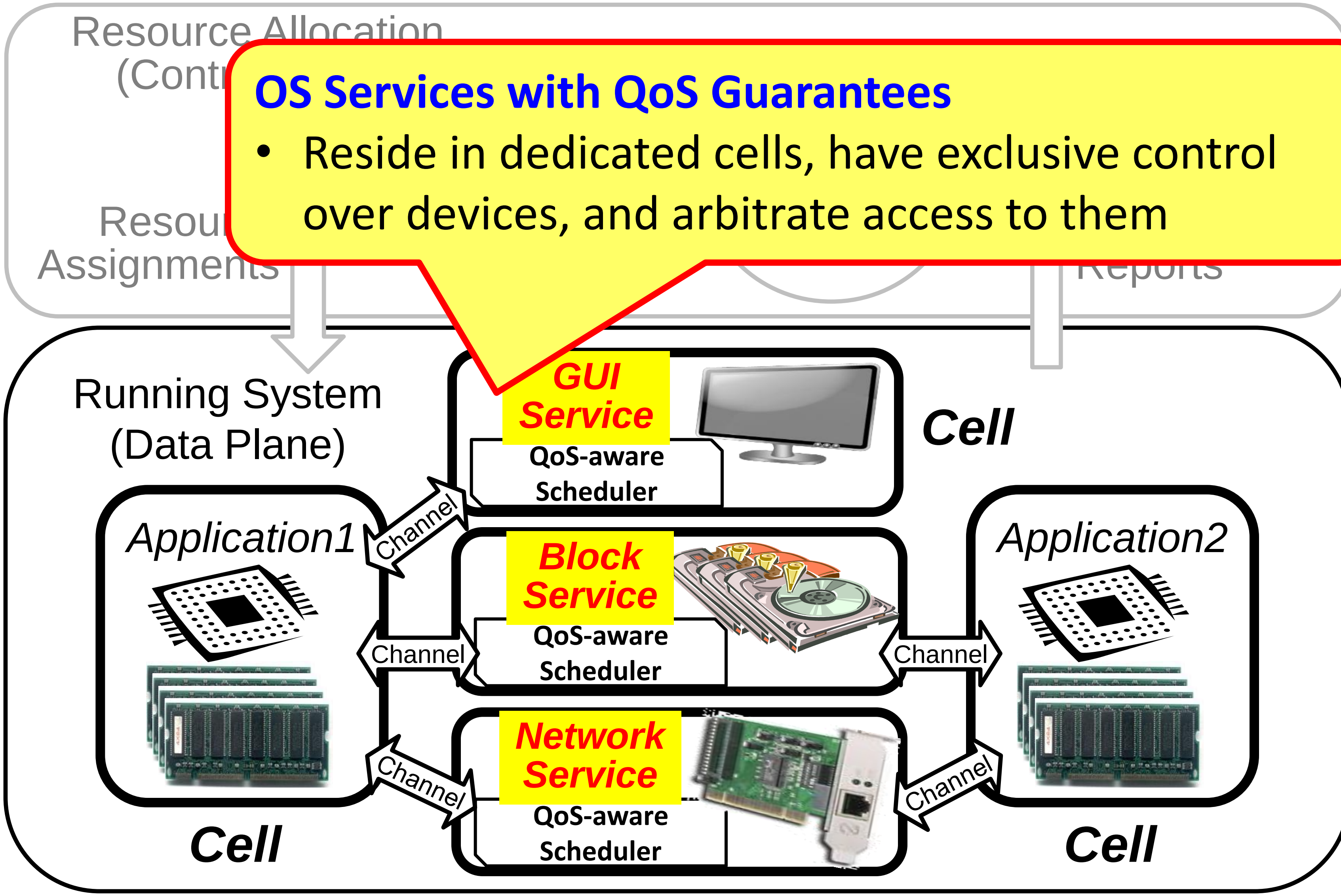
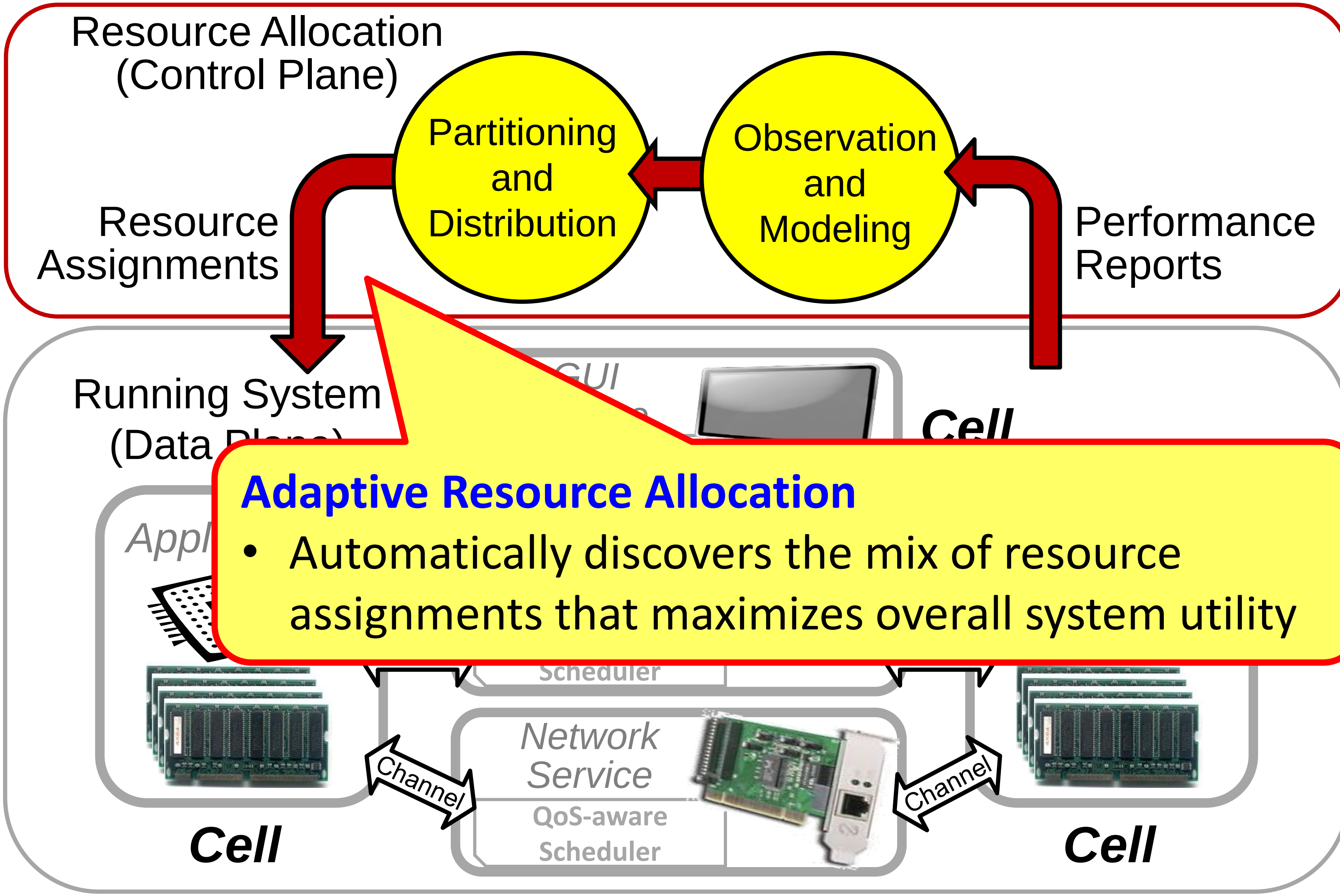


Adaptive Resource-Centric Computing (ARCC)



Adaptive Resource Allocation

- Automatically discovers the mix of resource assignments that maximizes overall system utility

Two-Level Scheduling

Split

Monolithic CPU and Resource Scheduling

into two pieces

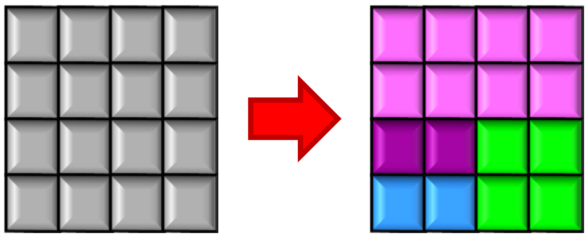
- Chunks of resources distributed to applications (Global Decisions)

Level 1
Coarse-grained Resource Allocation and Distribution

Level 2
Fine-grained Application-specific Scheduling

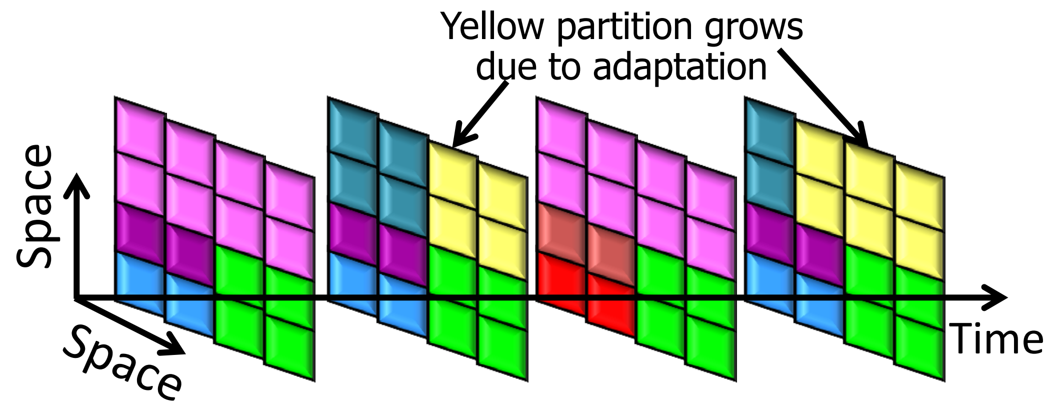
- Apps use their resources in any way they see fit (Local Decisions)

Space-Time Partitioning



Spatial Partition

- Key for performance isolation



Spatial partitioning is not static and may vary over time

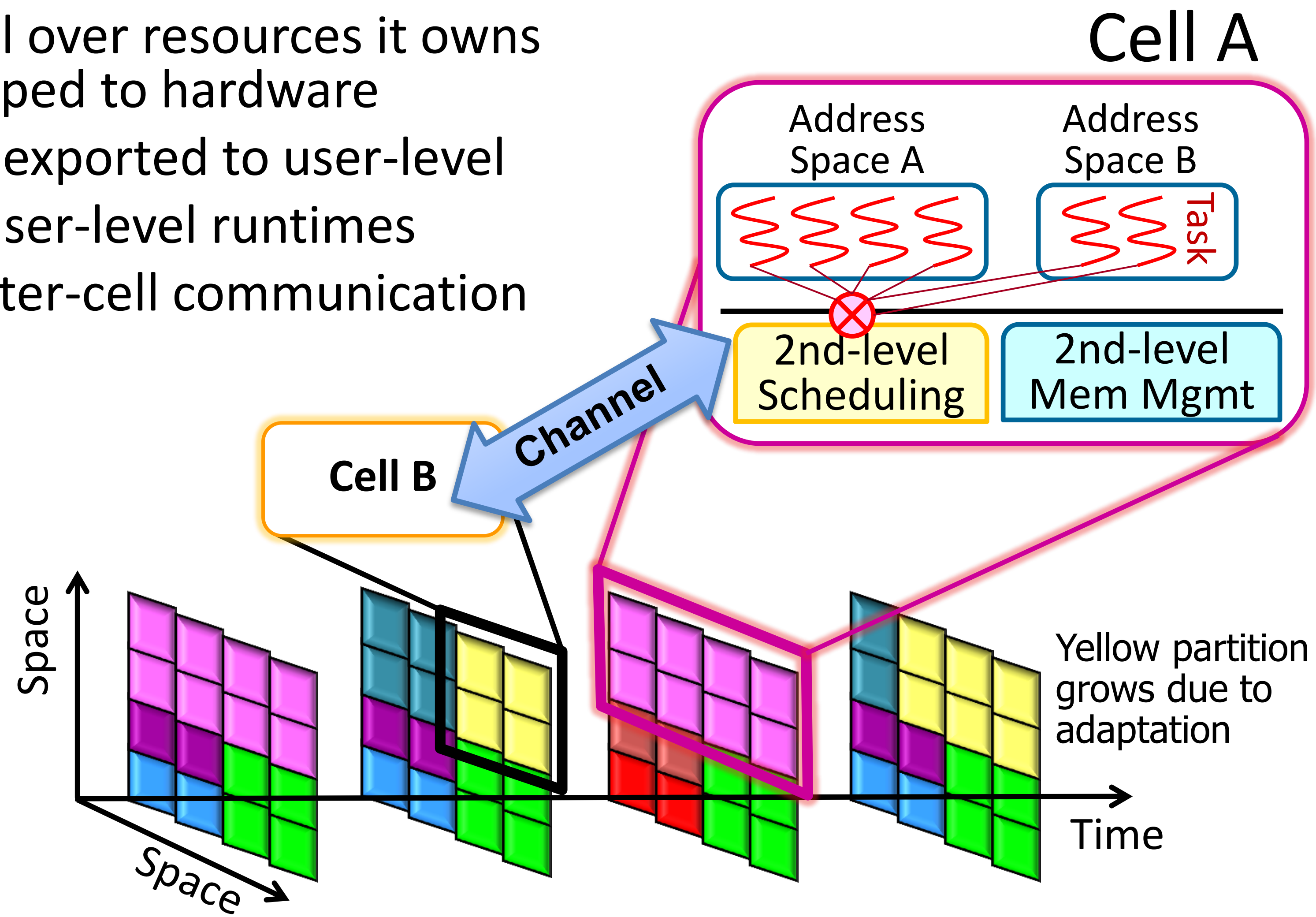
- Partitions can be time multiplexed; resources are **gang-scheduled**
- Partitioning adapts to system's needs

- Each partition receives a vector of basic resources
- A partition may also receive
  - Exclusive access to other resources (e.g., a device)
  - Guaranteed fractional services from other partitions

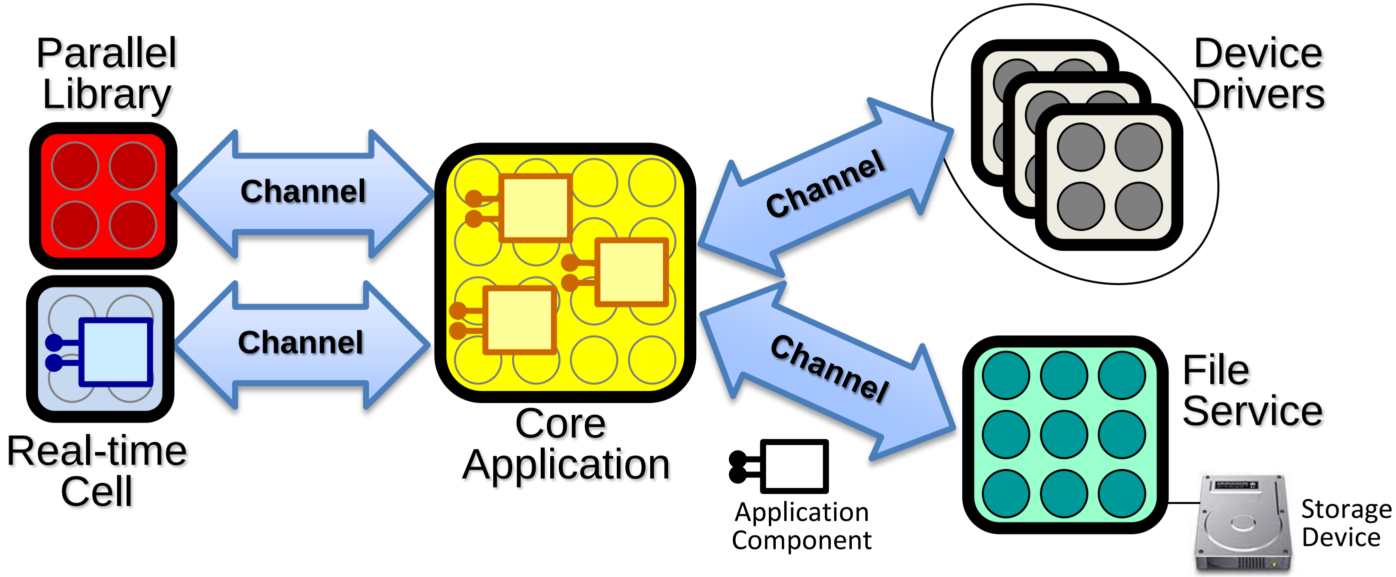
The Cell: Our Partitioning Abstraction

User-level Software Container with Guaranteed Access to Resources

- Full control over resources it owns when mapped to hardware
- Resources exported to user-level
- Adaptive user-level runtimes
- Efficient inter-cell communication channels



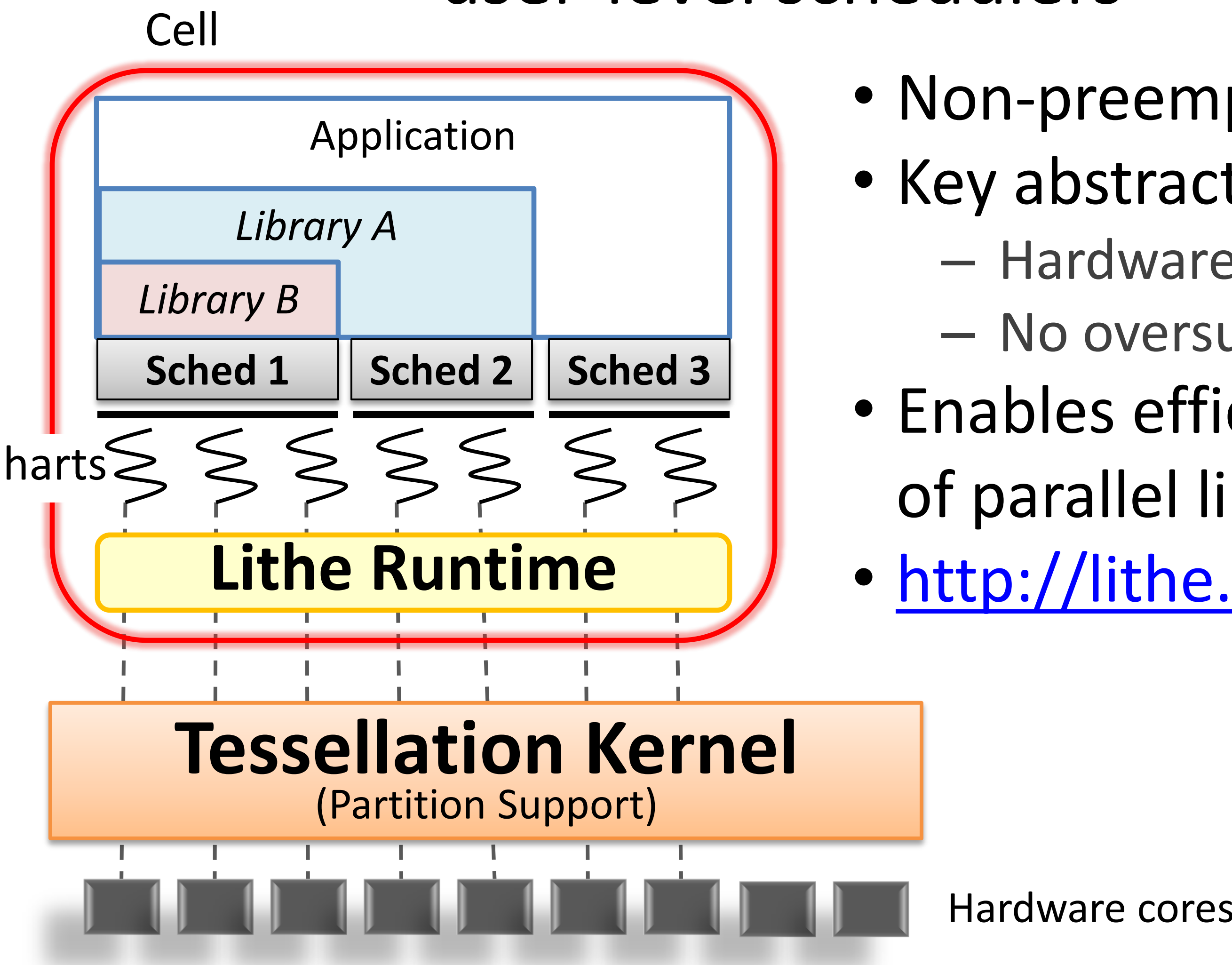
Basis of a Component-based Model
with Composable Performance



- Applications = Set of interacting components deployed on different cells
  - Applications split into performance-incompatible and mutually distrusting cells with controlled communication
  - OS Services are independent servers that provide QoS

Customizable User-Level Runtimes

Lithe: A framework for hierarchical cooperative user-level schedulers [PLDI'10]



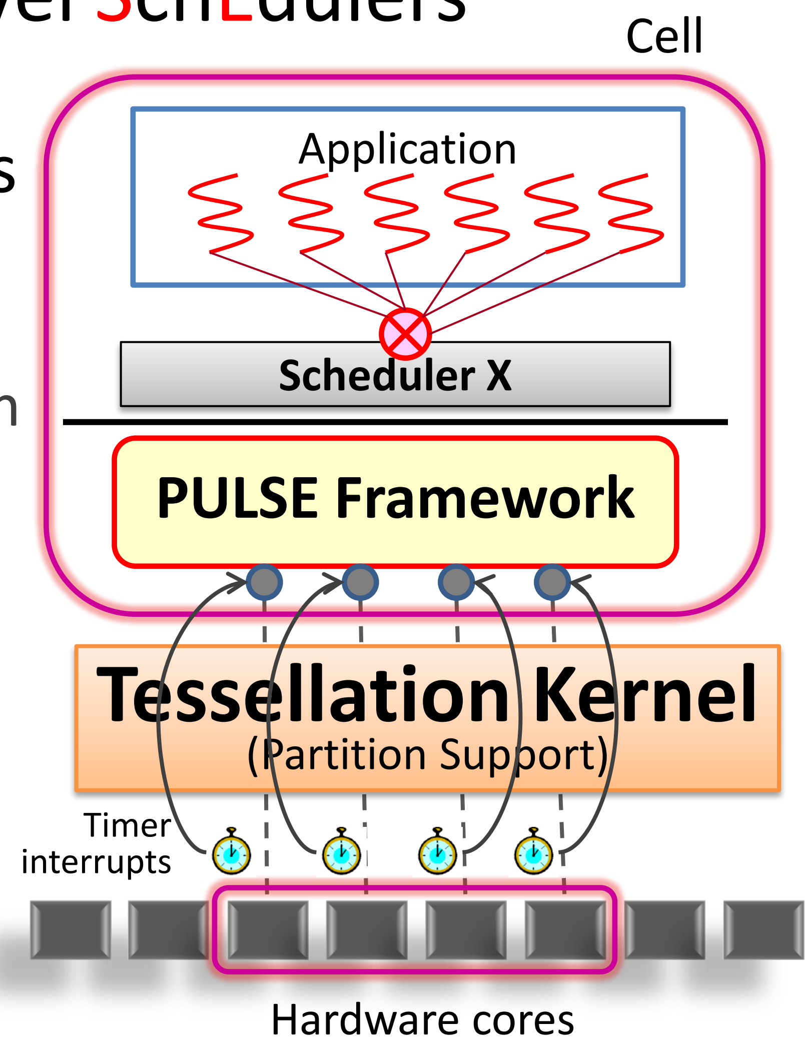
- Non-preemptive scheduling
- Key abstraction
  - Hardware threads (harts)
  - No oversubscription!
- Enables efficient composition of parallel libraries
- http://lithe.eecs.berkeley.edu

[PLDI'10] H. Pan, B. Hindman, K. Asanovic. *Composing parallel software efficiently with Lithe*.

Customizable User-Level Runtimes

PULSE: A framework for Preemptive User-Level SchEdulers

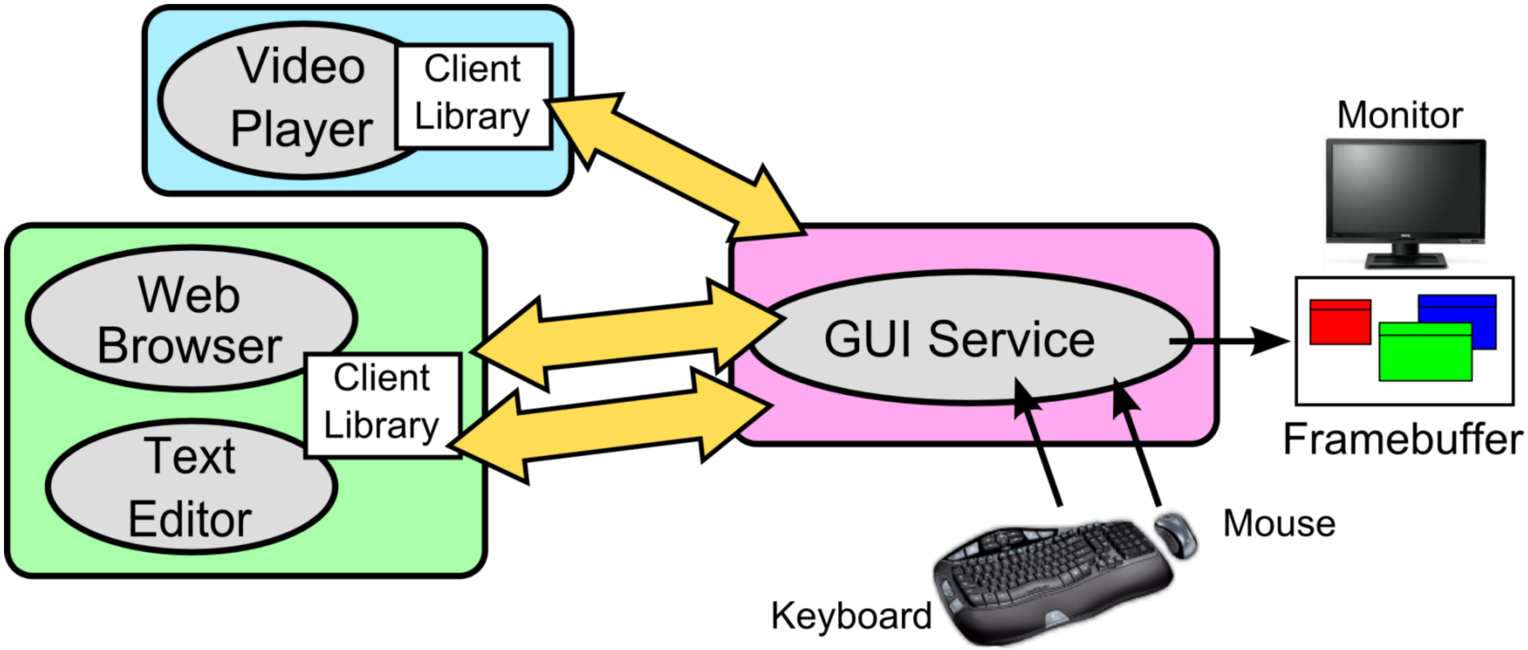
- Available preemptive schedulers
  - Round-robin (and pthreads)
  - EDF and Fixed Priority
  - Multiprocessor Constant Bandwidth Server (M-CBS) [ECRTS'04]
  - Juggle: A load balancer for SPMD applications [CLUSTER'12]
- Able to handle cell resizing



[ECRTS'04] S. Baruah et al. Executing aperiodic jobs in a multiprocessor constant-bandwidth server implementation. ECRTS'04.
[CLUSTER'12] S. Hofmeyr, J. Colmenares et al. *Juggle: Addressing extrinsic load imbalances in SPMD applications on multicore computers*. Cluster Computing Journal.

GUI Service [CATA' 12]

An OS Service with QoS Guarantees

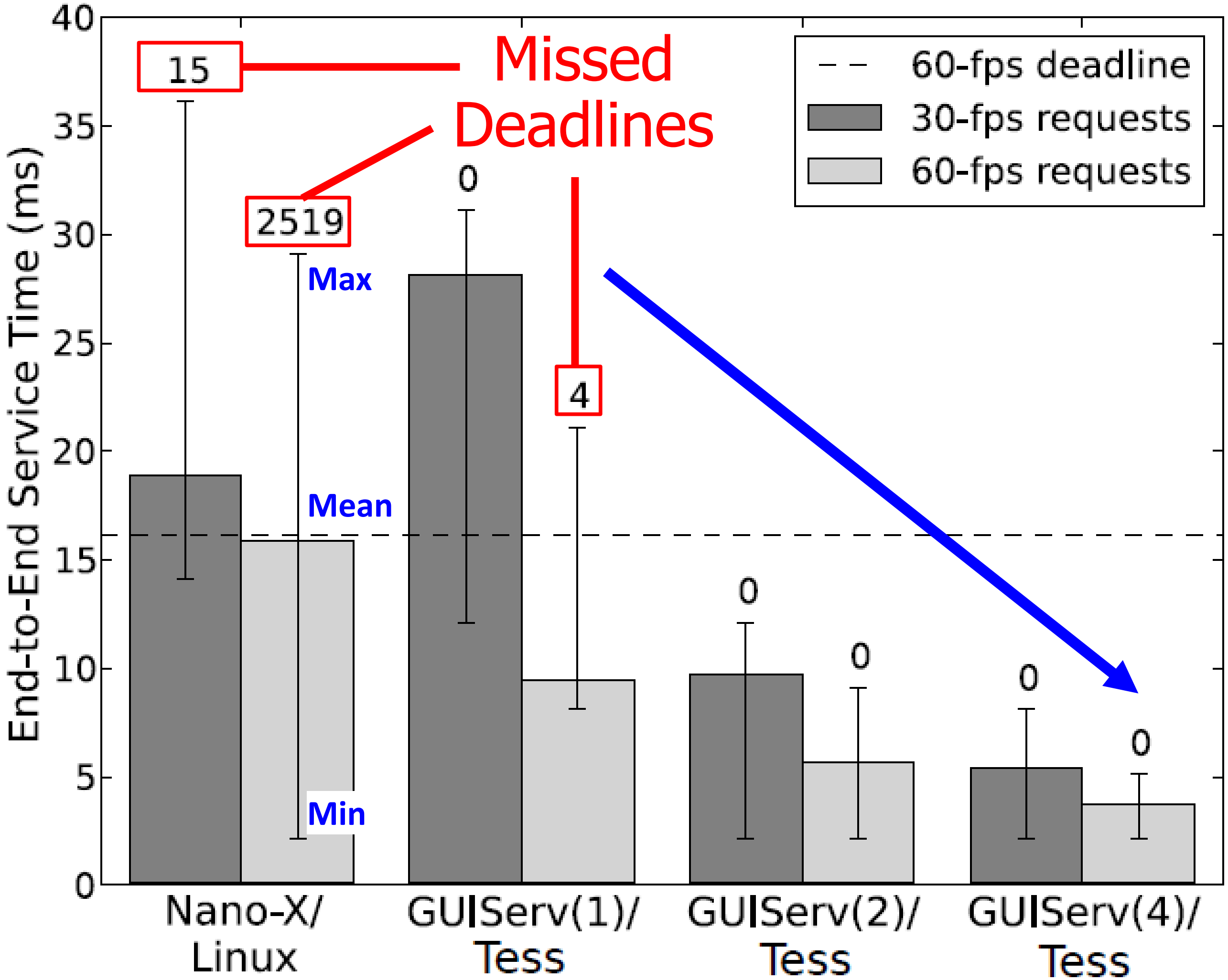


- Exploits task parallelism for improved service times
- Provides differentiated service to applications and soft service-time guarantees

[CATA'12] A. Kim, J. Colmenares, et al. *A soft real-time, parallel GUI service in Tessellation many-core OS*. [**Best Paper Award**]

Nano-X vs. GUI Service

Service times for 4 30-fps video players and 4 60-fps video players, each sending 1000 expensive requests



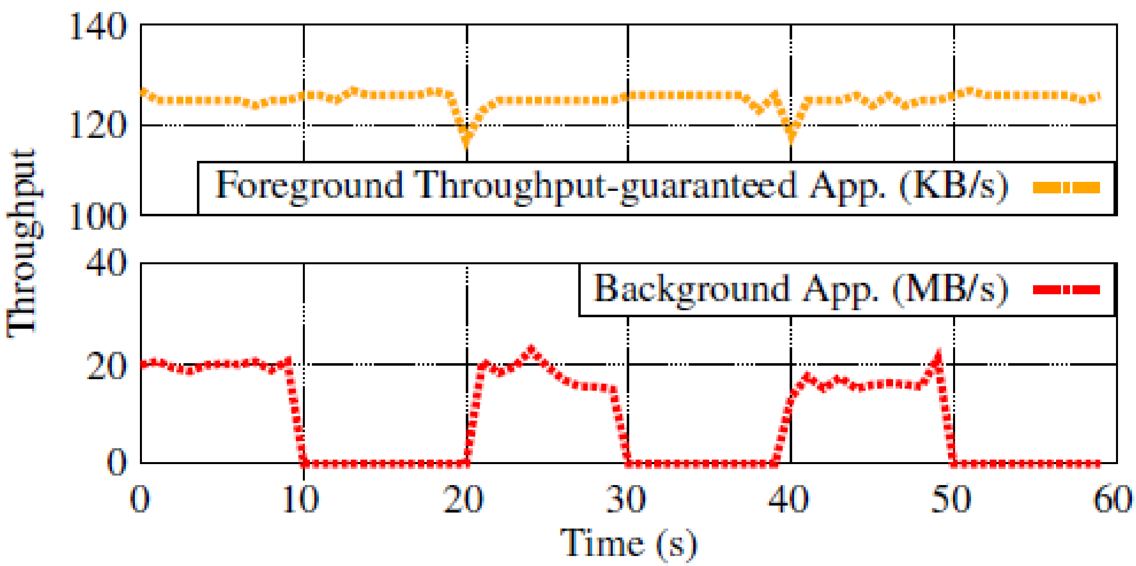
(#): Allocated hardware threads

Each bar represents 4 video clients. Above each bar is the total number of deadlines missed for the group.

Network Service [DAC'13, JAES'13]

An OS Service with QoS Guarantees

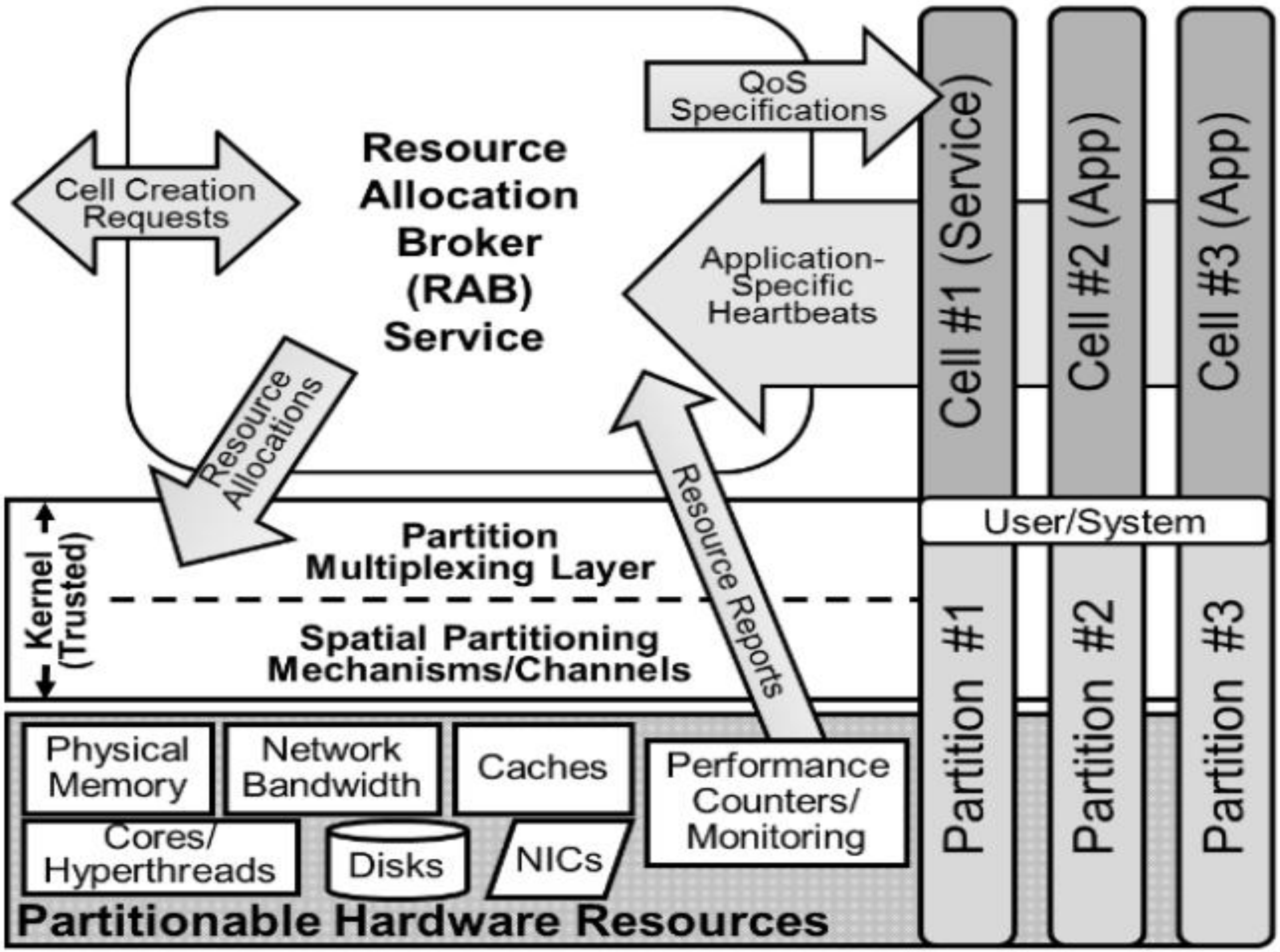
- Supports reservations and proportional share of bandwidth
  - Using mClock scheduling algorithm [OSDI'10] (on top of PULSE)
- NIC driver is entirely contained in user-space
  - No system calls when transmitting and receiving buffers



(Avg. throughput = 125.2 KB/s)

[DAC'13] J.A. Colmenares, G. Eads, et al. Tessellation: Refactoring the OS around explicit resource containers with continuous adaptation.
[JAES'13] J.A. Colmenares, G. Eads, et al. A multi-core operating system with QoS-guarantees for network audio applications.
[OSDI'10] A. Gulati et al. mClock: handling throughput variability for hypervisor IO scheduling.

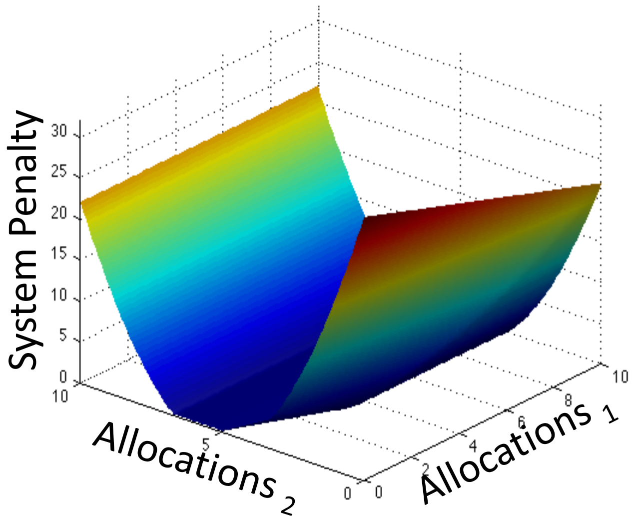
Adaptive Resource Allocation in Tessellation OS



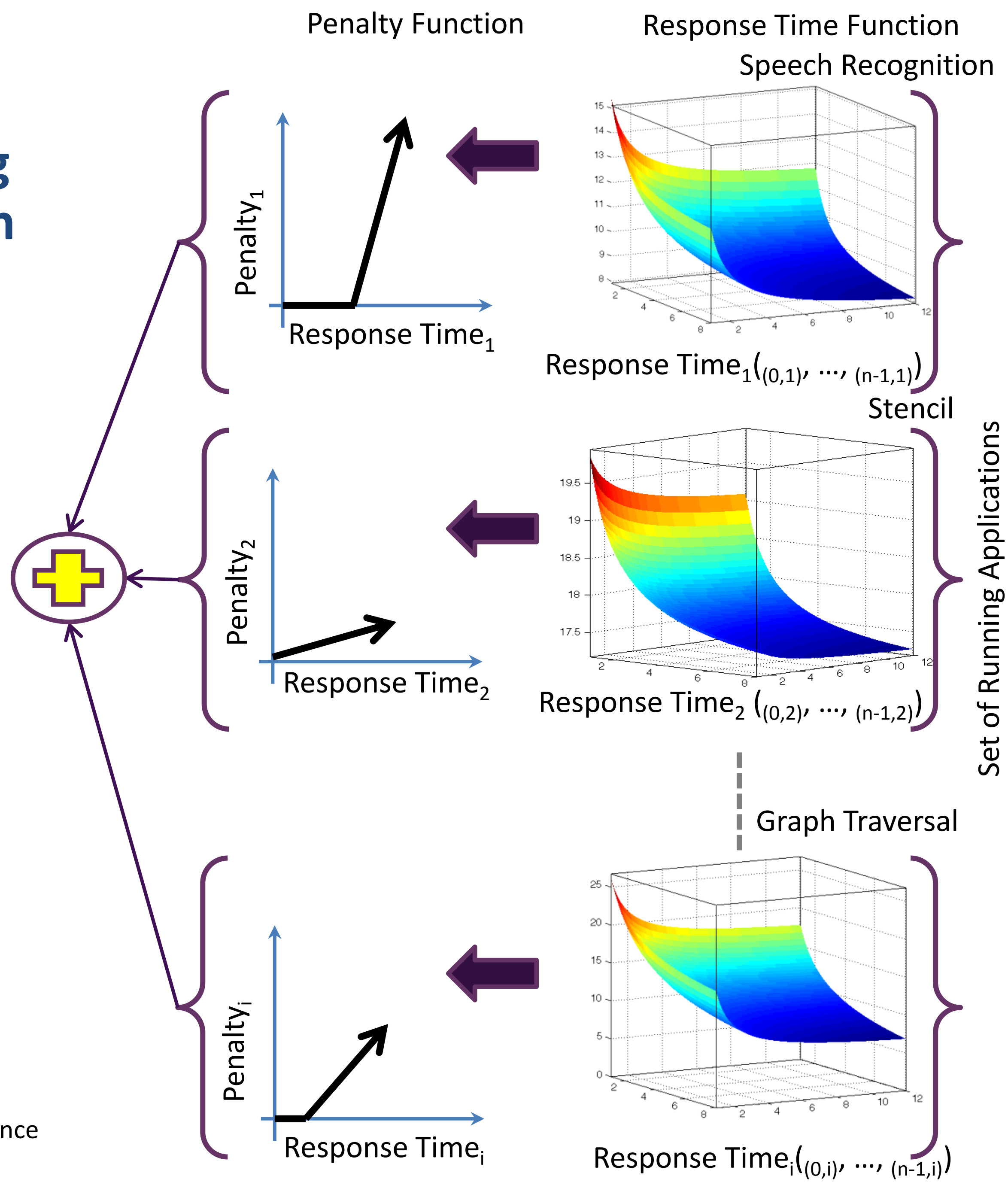
[DAC'13] J.A. Colmenares, G. Eads et al. Tessellation: Refactoring the OS around explicit resource containers with continuous adaptation.

PACORA

Resource Allocation using Convex Optimization with Online Application Performance Models



Continuously minimize the penalty of the system
(subject to restrictions on the total amount of resources)



[HOTPAR'11] S. Bird and B. Smith. PACORA: Performance aware convex optimization for resource allocation.

Known Facts and Lessons Learned

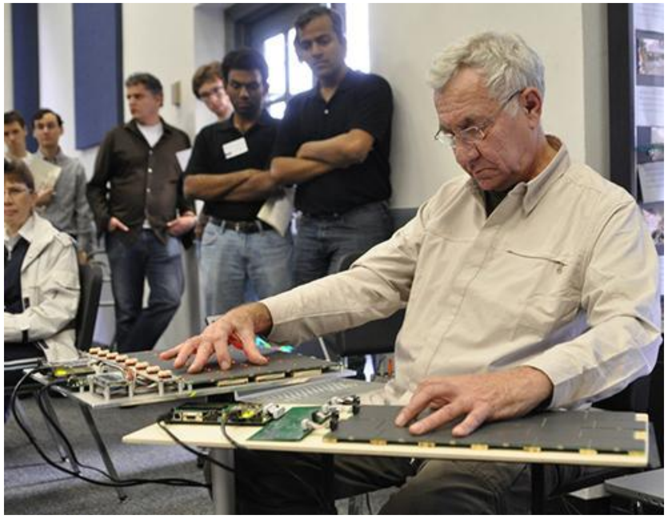
- [KF] Implementing an OS from scratch is challenging
- [KF] Supporting IO devices is very important
- [LL] Tessellation's structuring redistributes complexity
  - Lot of complexity moved from the kernel to user-level runtimes
  - Contending factor: overhead
- [LL] Having a simple kernel is very beneficial
  - Easier to reason about it, especially when providing performance guarantees
- [LL] Coordination between kernel and cell's user-level runtime is tricky (e.g., during cell resizing)
  - Not many LOCs, but very subtle issues and difficult to debug

Summary

- *Challenge*: Reinventing the OS for many-core platforms
  - Properly serve simultaneous applications of different types
  - Meet users' performance expectations
- *Approach*: Adaptive Resource-Centric Computing
  - Focuses on Space-Time Partitioning and Two-Level Scheduling
  - Includes
    - Cells: Resource containers
    - Customizable user-level runtimes
    - OS services with QoS guarantees
    - Adaptive resource allocation
- *Implementation*: Tess OS, Lithe, PULSE, and PACORA
- *Effectiveness*: Demonstrated in publications and demos!

Demos on Tessellation OS

- Adaptive Resource Centric Computing
  - Entirely on Tessellation
- Live Musical Performance
  - A synthesizer performing parallel real-time audio processing and controlled via the SLABS multi-touch interface
- Million Song Recommendation (Pardora) System
  - Specialized code on top of TBB/Lithe, plus python code
- Virtual Instrument
  - One of the backends



Next

- Demonstration of Adaptive Resource Centric Computing
  - Gage Eads and Sarah Bird, UC Berkeley
- Testimonial
  - Dave Probert, Microsoft

Adaptive Resource Centric Computing Demonstration

Adaptive Resource Centric Computing Demonstration

Network
(QoS from network service)

Cores
(QoS from kernel)

Bandwidth Hog

- TCP client application
- Single-threaded
- **Goal:** consume maximum bandwidth

Video Players
(1 vid per thread)

- Receives video stream from TCP connection
- 2 video sizes
- Performs H.264 decoding
- **Goal:** 30 FPS

psearchy

- Parallel file indexing benchmark
- Scalable work-queue based parallelism
- **Goal:** maximize indexing throughput

Come and see our demos!

Questions?

THANKS

Gang Scheduling in Tessellation

- No need of inter-core communication (in the common case) due to use of **synchronized clocks**
- Different time-multiplexing policies for cells