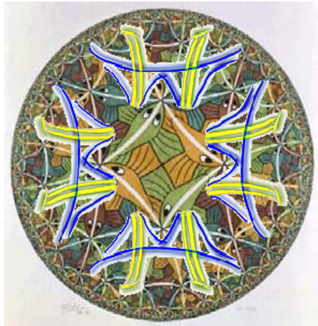
Tessellation OS



Architecting Systems Software in a ManyCore World

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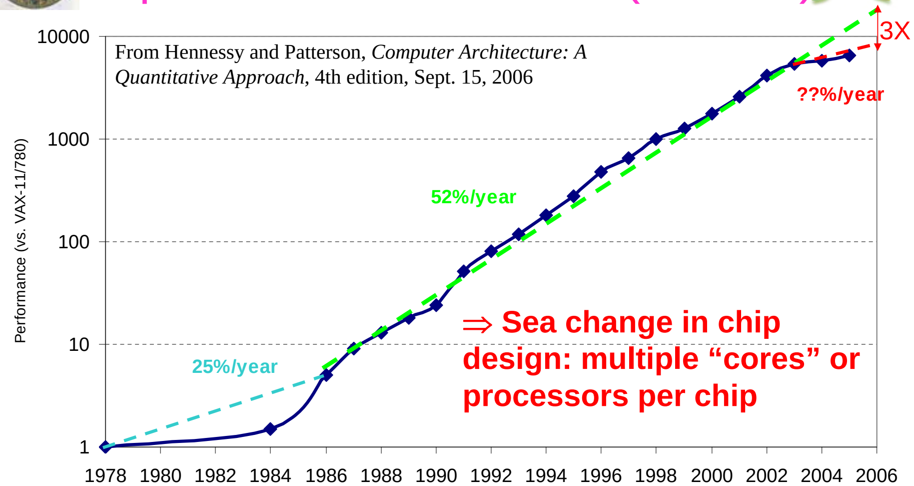
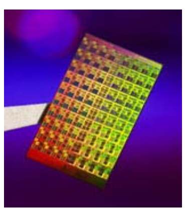
Uniprocessor Performance (SPECint)



- **VAX : 25%/year 1978 to 1986**
- **RISC + x86: 52%/year 1986 to 2002**
- **RISC + x86: ??%/year 2002 to present**

ManyCore Chips: The future is here



- Intel 80-core multicore chip (Feb 2007)
  - 80 simple cores
  - Two floating point engines /core
  - Mesh-like "network-on-a-chip"
  - 100 million transistors
  - 65nm feature size
- "ManyCore" refers to many processors/chip
  - 64? 128? Hard to say exact boundary
- How to program these?
  - Use 2 CPUs for video/audio
  - Use 1 for word processor, 1 for browser
  - 76 for virus checking???
- Something new is clearly needed here…

Parallel Processing for the Masses

- Why is the presence of ManyCore a problem?
  - Parallel computing has been around for 40 years with mixed results
    - Many researchers, several generations, widely varying approaches
  - Parallel computing has never become a generic software solution (especially for client applications)
  - Suddenly, parallel computing will appear at all levels of our computation stack
    - Cellphones
    - Cars (yes, Bosch is thinking of replacing some of the 70 processors in a high end car with ManyCore chips)
    - Laptops, Desktops, Servers…
- Time for the computer industry to panic a bit???
  - Perhaps

Why might we succeed this time?

- No Killer Microprocessor to Save Programmers (No Choice)
  - No one is building a faster serial microprocessor
  - For programs to go faster, SW must use parallel HW
- New Metrics for Success (Different Criteria)
  - Perhaps linear speedup is not the primary goal
  - Real Time Latency/Responsiveness and/or MIPS/Joule
  - Just need some new killer parallel apps vs. all legacy SW must achieve linear speedup
- Necessity: All the Wood Behind One Arrow (More Manpower)
  - Whole industry committed, so more working on it
  - If future growth of IT depends on faster processing at same price (vs. lowering costs like NetBook)
- User-Interactive Applications Exhibit Parallelism (New Apps)
  - Multimedia, Speech Recognition, situational awareness
- Multicore Synergy with Cloud Computing (Different Focus)
  - Cloud Computing apps parallel even if client not parallel
  - Manycore is cost-reduction, not radical SW disruption

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- What is the problem (Did this already)
- Berkeley Parlab
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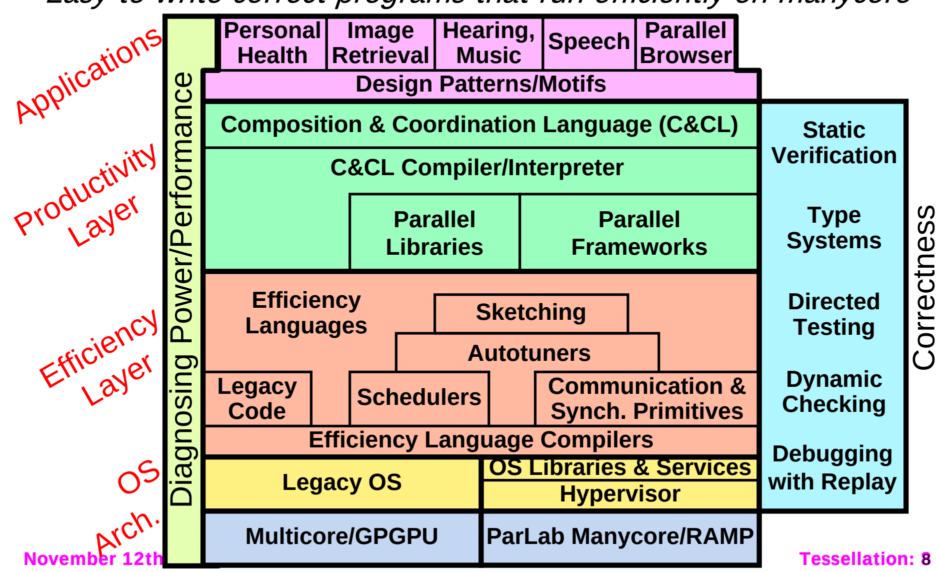
ParLab: a Fresh Approach to Parallelism

- What is the ParLAB?
  - A new Laboratory on Parallelism at Berkeley
    - Remodeled "open floorplan" space on 5th floor of Soda Hall
    - 10+ faculty, some two-feet in, others collaborating
  - Funded by Intel, Microsoft, and other affilliate partners
  - Goal: Productive, Efficient, Correct, Portable SW for 100+ cores & scale as core increase every 2 years (!)
  - Application Driven! (really!)
- Some History
  - Berkeley researchers from many backgrounds started meeting in Feb. 2005 to discuss parallelism
    - Circuit design, computer architecture, massively parallel computing, computer-aided design, embedded hardware and software, programming languages, compilers, scientific programming, and numerical analysis
    - Considered successes in high-performance computing (LBNL) and parallel embedded computing (BWRC)
  - Led to "Berkeley View" Tech. Report 12/2006 and new Parallel Computing Laboratory ("Par Lab")
    - Won invited competition form Intel/MS of top 25 CS Departments

Par Lab Research Overview

Easy to write correct programs that run efficiently on manycore



Target Environment: Client Computing

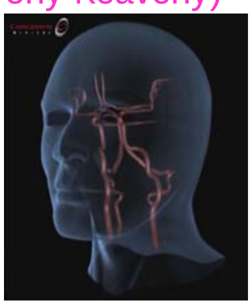
- ManyCore + Mobile Devices + Internet
  - Lots of Computational Resources
    - Must enable massive parallelism (not get in the way)
  - Many (relatively) Limited Resources:
    - Power, I/O bandwidth, Memory Bandwidth, User patience…
    - Must use these as efficiently as possible
  - Services backed by vast Internet resources
    - Information can be preserved elsewhere
    - Access to remote resources must be streamlined
    - Obvious use of ManyCore in Services – but this is not the real problem
- Things we are willing to change:
  - Software Engineering, Libraries, APIs, Services, Hardware

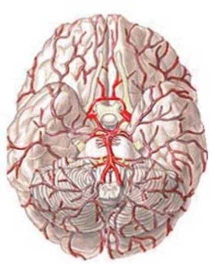
Music and Hearing Application (David Wessel)

- Musicians have an insatiable appetite for computation + real-time demands
  - More channels, instruments, more processing, more interaction!
  - Latency must be low (5 ms)
  - Must be reliable (No clicks!)
1. Music Enhancer
   - Enhanced sound delivery systems for home sound systems using large microphone and speaker arrays
   - Laptop/Handheld recreate 3D sound over ear buds
2. Hearing Augmenter
   - Handheld as accelerator for hearing aid
3. Novel Instrument User Interface
   - New composition and performance systems beyond keyboards
   - Input device for Laptop/Handheld

Berkeley Center for New Music and Audio Technology (CNMAT) created a compact loudspeaker array: 10-inch-diameter icosahedron incorporating 120 tweeters.

Health Application: Stroke Treatment (Tony Keaveny)





Bottom view of brain

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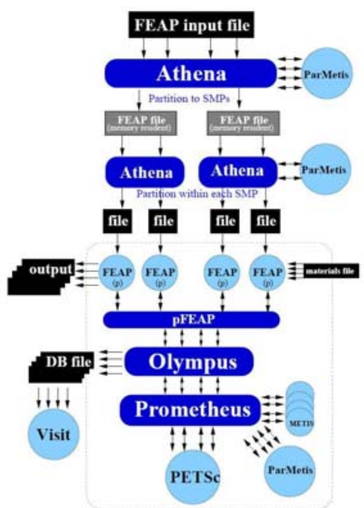
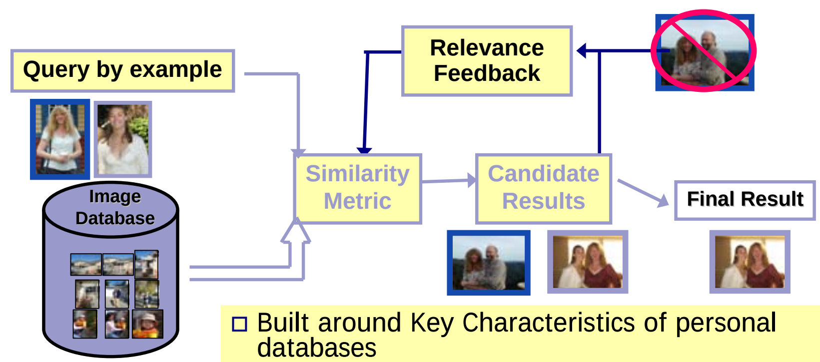


- Stroke treatment time-critical, need supercomputer performance in hospital
- Goal: First true 3D Fluid-Solid Interaction analysis of Circle of Willis
- Based on existing codes for distributed clusters

Content-Based Image Retrieval (Kurt Keutzer)



1000's of images

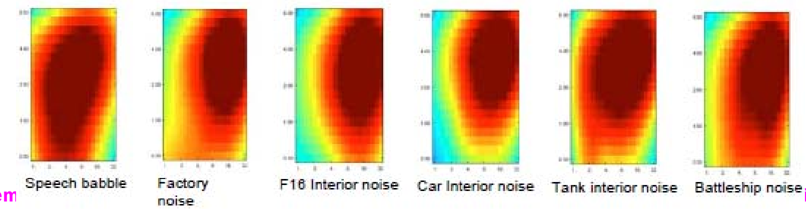
- Built around Key Characteristics of personal databases
  - Very large number of pictures (>5K)
  - Non-labeled images
  - Many pictures of few people
  - Complex pictures including people, events, places, and objects

Robust Speech Recognition

(Nelson Morgan)

- Meeting Diarist
  - Laptops/ Handhelds at meeting coordinate to create speaker identified, partially transcribed text diary of meeting

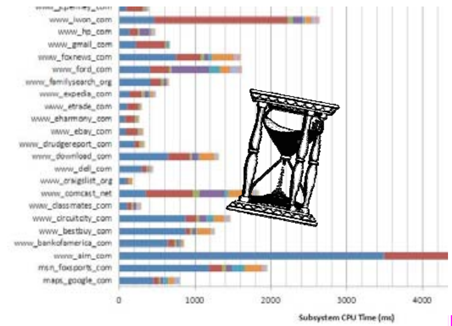
- Use cortically-inspired manystream spatio-temporal features to tolerate noise

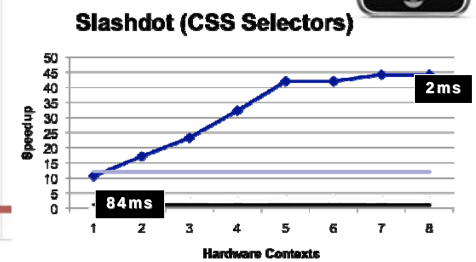


Parallel Browser

(Ras Bodik)

- Goal: Desktop quality browsing on handhelds
  - Enabled by 4G networks, better output devices
- Bottlenecks to parallelize
  - Parsing, Rendering, Scripting





Parallel Software Engineering

- How do we hope to tackle parallel programming?
  - Through Software Engineering and Control of Resources
- Two type of programmers:
  - Productivity programmers (90% of programmers)
    - Not parallel programmers, rather domain specific programmers
  - Efficiency programmers (10% of programmers)
    - Parallel programmers, extremely competent at handling parallel programming issues
- Target new ways to express software so that is can be execute in parallel
  - Parallel Patterns
- System support to avoid "getting in the way" of the result
  - Parallel Libraries, Autotuning, On-the-fly compilation
  - Explicitly managed resource containers (Partitions)

Architecting Parallel Software with Patterns (Kurt Keutzer/Tim Mattson)

Our initial survey of many applications brought out common recurring patterns:

"Dwarfs" -> Motifs

- Computational patterns
- Structural patterns

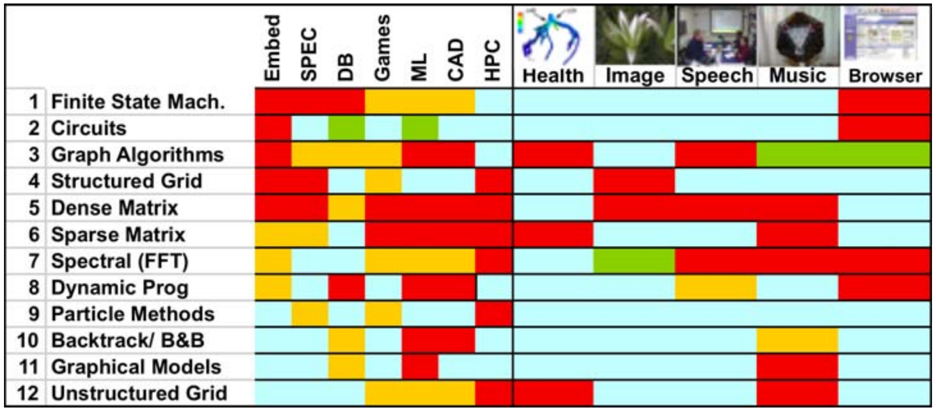
Insight: Successful codes have a comprehensible software architecture:

- Patterns give human language in which to describe architecture

Motif (nee "Dwarf") Popularity

(Red Hot / Blue Cool)

- How do compelling apps relate to 12 motifs?



Architecting Parallel Software

Decompose Tasks/Data

Order tasks **Identify Data Sharing and Access**

Identify the Software Structure

- •Pipe-and-Filter
- •Agent-and-Repository
- •Event-based
- •Bulk Synchronous
- •MapReduce
- •Layered Systems
- •Arbitrary Task Graphs

Identify the Key Computations

- Graph Algorithms
- Dynamic programming
- Dense/Spare Linear Algebra
- (Un)Structured Grids
- Graphical Models
- Finite State Machines
- Backtrack Branch-and-Bound
- N-Body Methods
- Circuits
- Spectral Methods

Par Lab is Multi-Lingual

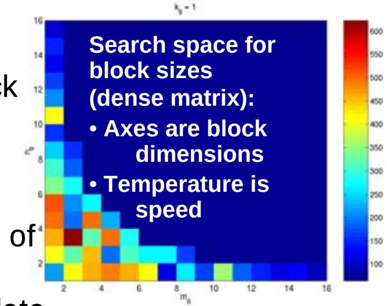
- Applications require ability to compose parallel code written in many languages and several different parallel programming models
  - Let application writer choose language/model best suited to task
  - High-level productivity code and low-level efficiency code
  - Old legacy code plus shiny new code
- Correctness through all means possible
  - Static verification, annotations, directed testing, dynamic checking
  - Framework-specific constraints on non-determinism
  - Programmer-specified semantic determinism
  - Require common spec between languages for static checker
- Common linking format at low level (Lithe) not intermediate compiler form
  - Support hand-tuned code and future languages & parallel models

Selective Embedded Just-In-Time Specialization (SEJITS) for Productivity (Armando Fox)

- Modern scripting languages (e.g., Python and Ruby) have powerful language features and are easy to use
- Idea: Dynamically generate source code in C within the context of a Python or Ruby interpreter, allowing app to be written using Python or Ruby abstractions but automatically generating, compiling C at runtime
- Like a JIT but
  - **Selective**: Targets a particular method and a particular language/platform (C+OpenMP on multicore or CUDA on GPU)
  - **Embedded**: Make specialization machinery productive by implementing in Python or Ruby itself by exploiting key features: introspection, runtime dynamic linking, and foreign function interfaces with language-neutral data representation

Autotuning for Code Generation (Demmel, Yelick)

- Problem: generating optimal code like searching for needle in haystack
- Manycore ➔ even more diverse
- New approach: "Auto-tuners"
  - 1st generate program variations of combinations of optimizations (blocking, prefetching, …) and data structures
  - Then compile and run to heuristically search for best code for *that* computer
- Examples: PHiPAC (BLAS), Atlas (BLAS), Spiral (DSP), FFT-W (FFT)



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Services Support for Applications

- What systems support do we need for new ManyCore applications?
  - Should we just port parallel Linux or Windows 7 and be done with it?
- Clearly, these new applications will contain:
  - Explicitly parallel components
    - However, parallelism may be "hard won" (not embarrassingly parallel)
    - Must not interfere with this parallelism
  - Direct interaction with Internet 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

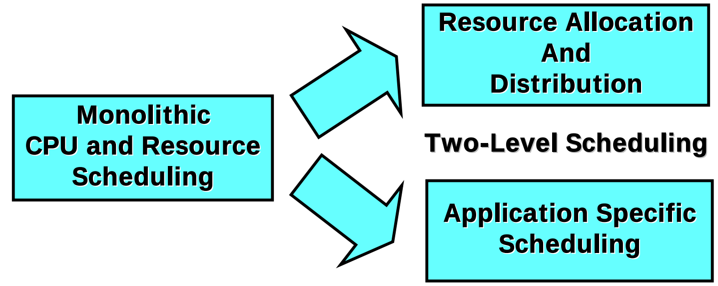
PARLab OS Goals: *RAPPidS*

- Responsiveness: Meets real-time guarantees
  - Good user experience with UI expected
  - Illusion of Rapid I/O while still providing guarantees
  - Real-Time applications (speech, music, video) will be assumed
- Agility: Can deal with rapidly changing environment
  - Programs not completely assembled until runtime
  - User may request complex mix of services at moment's notice
  - Resources change rapidly (bandwidth, power, etc)
- Power-Efficiency: Efficient power-performance tradeoffs
  - Application-Specific parallel scheduling on Bare Metal partitions
  - Explicitly parallel, power-aware OS service architecture
- Persistence: User experience persists across device failures
  - Fully integrated with persistent storage infrastructures
  - Customizations not be lost on "reboot"
- Security and Correctness: Must be hard to compromise
  - Untrusted and/or buggy components handled gracefully
  - Combination of *verification* and *isolation* at many levels
  - Privacy, Integrity, Authenticity of information asserted

The Problem with Current OSs

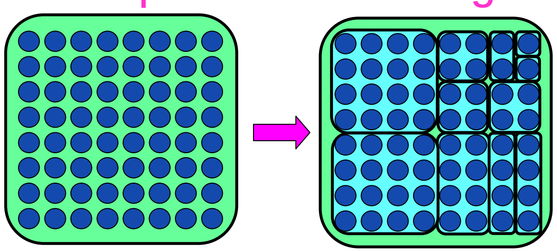
- What is wrong with current Operating Systems?
  - They do not allow expression of application requirements
    - Minimal Frame Rate, Minimal Memory Bandwidth, Minimal QoS from system Services, Real Time Constraints, …
    - No clean interfaces for reflecting these requirements
  - They do not provide guarantees that applications can use
    - They do not provide performance isolation
    - Resources can be removed or decreased without permission
    - Maximum response time to events cannot be characterized
  - They do not provide fully custom scheduling
    - In a parallel programming environment, ideal scheduling can depend crucially on the programming model
  - They do not provide sufficient Security or Correctness
    - Monolithic Kernels get compromised all the time
    - Applications cannot express domains of trust within themselves without using a heavyweight process model
- The advent of ManyCore both:
  - Exacerbates the above with a greater number of shared resources
  - Provides an opportunity to change the fundamental model

A First Step: Two Level Scheduling



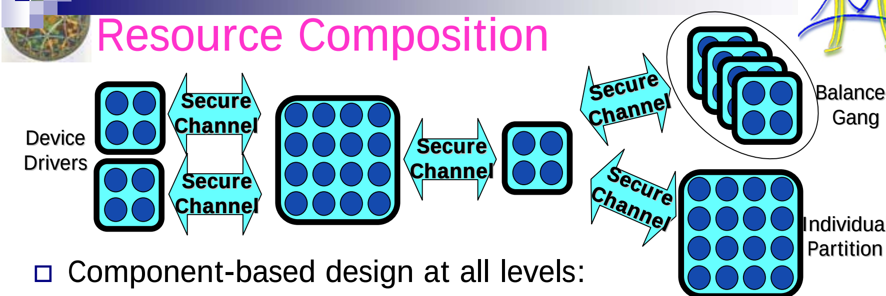
- Split monolithic scheduling into two pieces:
  - Course-Grained Resource Allocation and Distribution
    - Chunks of resources (CPUs, Memory Bandwidth, QoS to Services) distributed to application (system) components
    - Option to simply turn off unused resources (Important for Power)
  - Fine-Grained Application-Specific Scheduling
    - Applications are allowed to utilize their resources in any way they see fit
    - Other components of the system cannot interfere with their use of resources

Important Mechanism: Spatial Partitioning



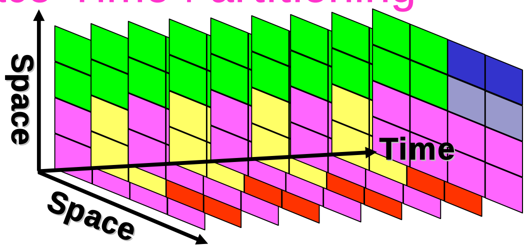
- Spatial Partition: group of processors acting within hardware boundary
  - Boundaries are "hard", communication between partitions controlled
  - Anything goes within partition
- Each Partition receives a *vector* of resources
  - Some number of dedicated processors
  - Some set of dedicated resources (exclusive access)
    - Complete access to certain hardware devices
    - Dedicated raw storage partition
  - Some guaranteed fraction of other resources (QoS guarantee):
    - Memory bandwidth, Network bandwidth
    - fractional services from other partitions

Resource Composition



- Component-based design at all levels:
  - Applications consist of interacting components
  - Requires composable: Performance, Interfaces, Security
- Spatial Partitioning Helps:
  - Protection of computing resources not required within partition
    - High walls between partitions $\Rightarrow$ anything goes within partition
    - "Bare Metal" access to hardware resources
    - Shared Memory/Message Passing/whatever within partition
  - Partitions exist simultaneously $\Rightarrow$ fast inter-domain communication
    - Applications split into mutually distrusting partitions w/ controlled communication (echoes of μKernels)
    - Hardware acceleration/tagging for fast secure messaging

Space-Time Partitioning



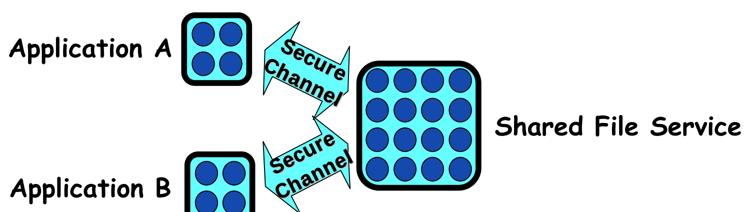
- Spatial Partitioning Varies over Time
  - Partitioning adapts to needs of the system
  - Some partitions persist, others change with time
  - Further, Partititions can be Time Multiplexed
    - Services (i.e. file system), device drivers, hard realtime partitions
    - Some user-level schedulers will time-multiplex threads within a partition
- Global Partitioning Goals:
  - Power-performance tradeoffs
  - Setup to achieve QoS and/or Responsiveness guarantees
  - Isolation of real-time partitions for better guarantees

Another Look: Two-Level Scheduling

- First Level: Gross partitioning of resources
  - Goals: Power Budget, Overall Responsiveness/QoS, Security
  - Partitioning of CPUs, Memory, Interrupts, Devices, other resources
  - Constant for sufficient period of time to:
    - Amortize cost of global decision making
    - Allow time for partition-level scheduling to be effective
  - Hard boundaries ⇒ interference-free use of resources for quanta
    - Allows AutoTuning of code to work well in partition
- Second Level: Application-Specific Scheduling
  - Goals: Performance, Real-time Behavior, Responsiveness, Predictability
  - CPU scheduling tuned to specific applications
  - Resources distributed in application-specific fashion
  - External events (I/O, active messages, etc) deferrable as appropriate
- Justifications for two-level scheduling?
  - Global/cross-app decisions made by 1st level
    - E.g. Save power by focusing I/O handling to smaller number of cores
  - App-scheduler (2nd level) better tuned to application
    - Lower overhead/better match to app than global scheduler
    - No global scheduler could handle all applications

It's all about the communication

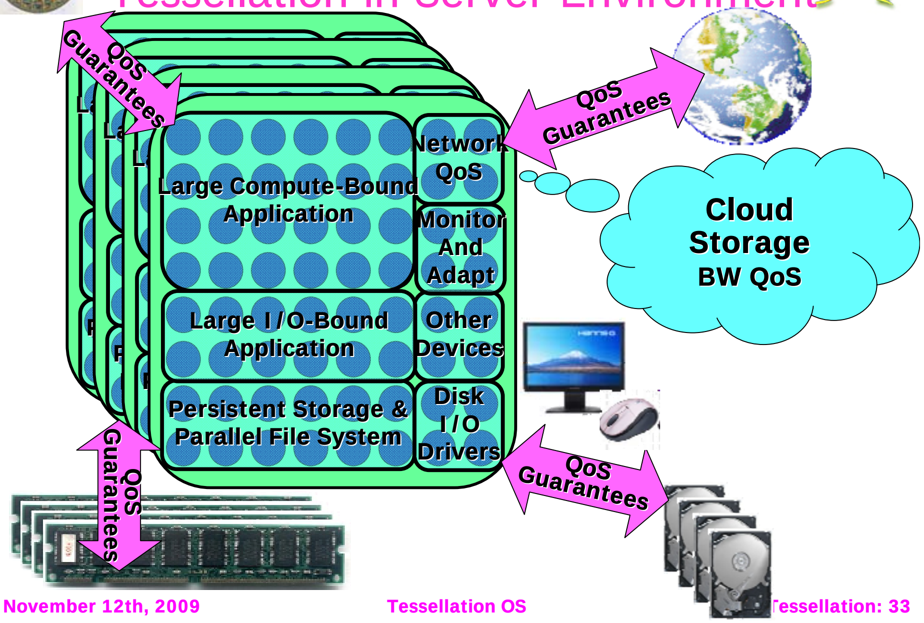
- We are interested in communication for many reasons:
  - Communication represents a security vulnerability
  - Quality of Service (QoS) boils down message tracking
  - Communication efficiency impacts decomposability
- Shared components complicate resource isolation:
  - Need distributed mechanism for tracking and accounting of resource usage
    - E.g.: How do we guarantee that each partition gets a guaranteed fraction of the service:



Tessellation: The Exploded OS

- Normal Components split into pieces
  - Device drivers (Security/Reliability)
  - Network Services (Performance)
    - TCP/IP stack
    - Firewall
    - Virus Checking
    - Intrusion Detection
  - Persistent Storage (Performance, Security, Reliability)
  - Monitoring services
    - Performance counters
    - Introspection
  - Identity/Environment services (Security)
    - Biometric, GPS, Possession Tracking
- Applications Given Larger Partitions
  - Freedom to use resources arbitrarily

Tessellation in Server Environment



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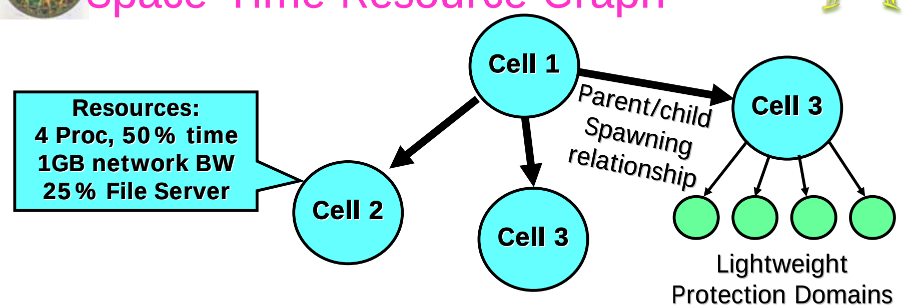
Defining the Partitioned Environment

- Cell: a bundle of code, with guaranteed resources, running at user level
  - Has full control over resources it owns ("Bare Metal")
  - Contains at least one address space (memory protection domain), but could contain more than one
  - Contains a set of secured channel endpoints to other Cells
  - Interacts with trusted layers of Tessellation (e.g. the "NanoVisor") via a heavily Paravirtualized Interface
    - E.g. Can manipulate its address mappings but does not know what page tables even look like
  - We think of these as components of an application or the OS
- When mapped to the hardware, a cell gets:
  - Gang-schedule hardware thread resources ("Harts")
  - Guaranteed fractions of other physical resources
    - Physical Pages (DRAM), Cache partitions, memory bandwidth, power
  - Guaranteed fractions of system services

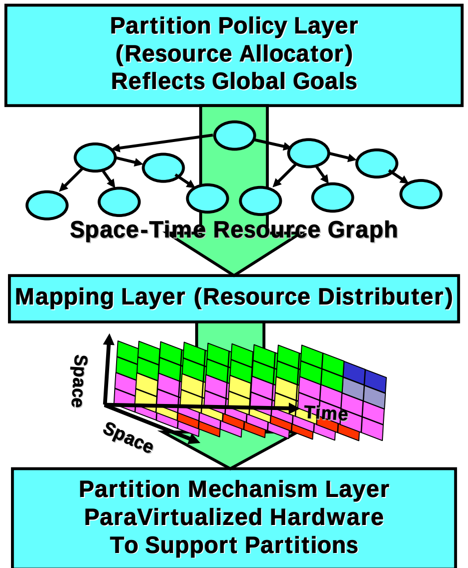
Space-Time Resource Graph



- Space-Time resource graph: the explicit instantiation of resource assignments
  - Directed Arrows Express Parent/Child Spawning Relationship
  - All resources have a Space/Time component
    - E.g. X Processors/fraction of time, or Y Bytes/Sec
- What does it mean to give resources to a Cell?
  - The Cell has a position in the Space-Time resource graph and
  - The resources are added to the cell's resource label
  - Resources cannot be taken away except via explicit APIs

Implementing the Space-Time Graph

- Partition Policy layer (allocation)
  - Allocates Resources to Cells based on Global policies
  - Produces only implementable space-time resource graphs
  - May deny resources to a cell that requests them (admission control)
- Mapping layer (distribution)
  - Makes no decisions
  - Time-Slices at a course granularity (when time-slicing necessary)
  - performs bin-packing like operation to implement space-time graph
  - In limit of *many* processors, no time multiplexing processors, merely distributing resources
- Partition Mechanism Layer
  - Implements hardware partitions and secure channels
  - Device Dependent: Makes use of more or less hardware support for QoS and Partitions



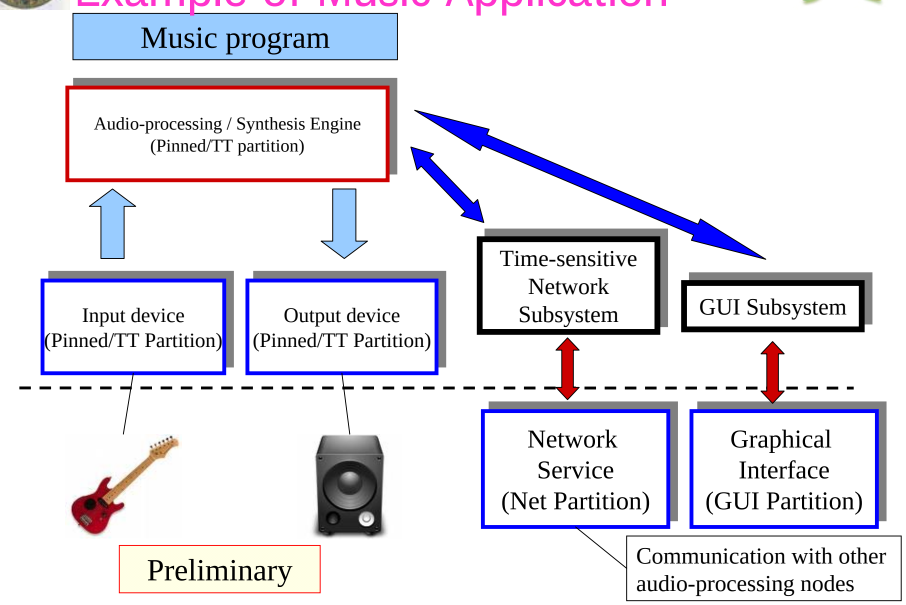
What happens in a Cell Stays in a Cell

- Cells are performance and security isolated from all other cells
  - Processors and resources are gang-scheduled
    - All fine-grained scheduling done by a user-level scheduler
  - Unpredictable resource virtualization does not occur
    - Example: no paging without linking a paging library
  - Cells can control delivery of all events
    - Message arrivals (along channels)
    - Page faults, timer interrupts (for user-level preemptive scheduling), exceptions, etc
  - Cells start with single protection domain, but can request more as desired
    - Initial protection domain becomes primary
    - For now, protection domains are Address Spaces, but can be other things as well
- CellOS: A layer of code within a Cell that looks like a traditional OS
  - Not required for all Cells!
  - On Demand Paging, Address Space management, Preemptive scheduling of multiple address spaces (i.e. processes)

Scheduling inside a cell

- Cell Scheduler can rely on:
  - Course-grained time quanta allowing efficient fine-grained use of resources
  - Gang-Scheduling of processors within a cell
  - No unexpected removal of resources
  - Full Control over arrival of events
    - Can disable events, poll for events, etc.
- Application-specific scheduling for performance
  - Lithe Scheduler Framework (for constructing schedulers)
  - Systematic mechanism for building composable schedulers
    - Parallel libraries with completely different parallelism models can be easily composed
- Application-specific scheduling for Real-Time
  - Label Cell with Time-Based Labels. Examples:
    - Run every 1s for 100ms synchronized to ± 5ms of a global time base
    - Pin a cell to 100% of some set of processors
  - Then, maintain own deadline scheduler
- Pure environment of a Cell ⇒ Autotuning will return same performance at runtime as during training phase

Example of Music Application



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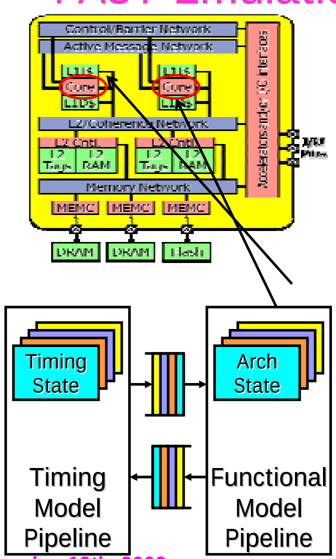
What would we like from the Hardware?

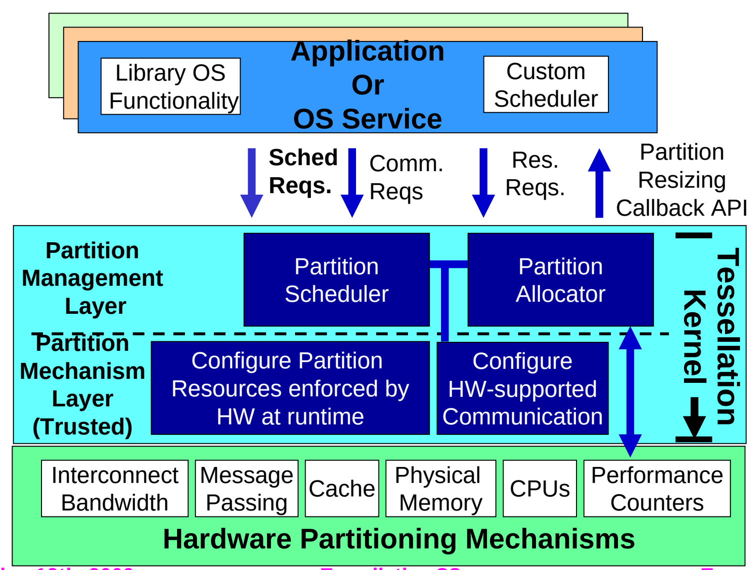
- A good parallel computing platform (Obviously!)
  - Good synchronization, communication
    - On chip ⇒ Can do fast barrier synchronization with combinational logic
    - Shared memory relatively easy on chip
  - Vector, GPU, SIMD
    - Can exploit data parallel modes of computation
  - Measurement: performance counters
- Partitioning Support
  - Caches: Give exclusive chunks of cache to partitions
    - Techniques such as page coloring are poor-man's equivalent
  - Memory: Ability to restrict chunks of memory to a given partition
    - Partition-physical to physical mapping: 16MB page sizes?
  - High-performance barrier mechanisms partitioned properly
  - System Bandwidth
  - Power
    - Ability to put partitions to sleep, wake them up quicly
- Fast messaging support
  - Used for inter-partition communication
  - DMA, user-level notification mechanisms
  - Secure Tagging?
- QoS Enforcement Mechanisms
  - Ability to give restricted fractions of bandwidth
  - Message Interface: Tracking of message rates with source-suppression for QoS
  - Examples: Globally Synchronized Frames (ISCA 2008, Lee and Asanovic)

RAMP Gold: FAST Emulation of new Hardware



- RAMP emulation model for Parlab manycore
  - SPARC v8 ISA -> v9
  - Considering ARM model
- Single-socket manycore target
- Split functional/timing model, both in hardware
  - Functional model: Executes ISA
  - Timing model: Capture pipeline timing detail (can be cycle accurate)
- Host multithreading of both functional and timing models
- Built for Virtex-5 systems (ML505 or BEE3)

Tessellation Architecture



Tessellation Implementation Status

- First version of Tessellation
  - ~7000 lines of code in NanoVisor layer
  - Supports basic partitioning
    - Cores and caches (via page coloring)
    - Fast inter-partition channels (via ring buffers in shared memory, soon cross-network channels)
  - Network Driver and TCP/IP stack running in partition
    - Devices and Services available across network
  - Hard Thread interface to Lithe – a framework for constructing user-level schedulers
- Currently Two ports
  - 4-core Nehalem system
  - 64-core RAMP emulation of a manycore processor (SPARC)
    - Will allow experimentation with new hardware resources
    - Examples:
      - QoS Controlled Memory/Network BW
      - Cache Partitioning
      - Fast Inter-Partition Channels with security tagging

Conclusion

- Berkeley ParLAB
  - Application Driven: New exciting parallel applicatoins
  - Tackling the parallel programming problem via Software Engineering
  - Parallel Programming Motifs
- Space-Time Partitioning: grouping processors & resources behind hardware boundary
  - Focus on Quality of Service
  - Two-level scheduling
    1) Global Distribution of resources
    2) Application-Specific scheduling of resources
  - Bare Metal Execution within partition
  - Composable performance, security, QoS
- Tessellation OS