Converging Interconnect Fabric Requirements for HPC and Warehouse Scale Computing

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Overview

- **HPC Application Performance in the Cloud**
  - **Hardware**: is cloud correctly formulated for HPC?
  - **Software**: are HPC apps correctly formulated for the cloud?
- **Use similar CPU's, but HPC/Cloud fabric requirements diverge**
  - **Old CW**: Cloud/datacenter requirements not aligned with HPC
  - **New CW**: Cloud requirements are more aligned than ever with HPC requirements
- **HW: New Cloud fabrics closer to HPC requirements**
  - Converging on high-performance internal networks
  - Still divergent on variability and fault recovery
- **SW: New formulations of HPC apps. closer to Cloud requirements**
  - Even exascale machines will have high variability & fault rates
  - Potential solutions would benefit both environments
  - But formulation requires fundamental rethink of math & algorithms

Measuring Cloud Value Proposition (2009)

- **Evaluate the effectiveness of Clouds for HPC**
  - Potentially replace DOE HPC Centers with credits in the "cloud"
- **Performance Barometer: Performance of HPC apps in the cloud**
  - What was the original cloud value proposition (circa 2009)

- **Convergent requirements for processors**
  - Massive parallelism
  - COTS x86 nodes
- **Divergence requirements for fabrics**
  - **Cloud**: externally facing TPC/IP standard fabrics
  - **HPC**: internally facing high performance custom fabrics

Using HPC Workload to Assess Performance

(NERSC Sustained System Performance/SSP)

SSP represents delivered performance for a real workload

CAM Climate	*GAMESS* Quantum Chemistry	*GTC* Fusion	*IMPACT-T* Accelerator Physics	*MAESTRO* Astro-physics	*MILC* Nuclear Physics	*PARATEC* Material Science

- **SSP: aggregate measure of the workload-specific, delivered performance of a computing system**
- **For each code measure**
  - **FLOP counts on a reference system**
  - **Wall clock run time on various systems**
  - ***N* chosen to be 3,200**
- **Problem sets drastically reduced for cloud benchmarking**

$$SSP = N \left(\prod_{i=1}^{M} P_i \right)^{(1/M)}$$

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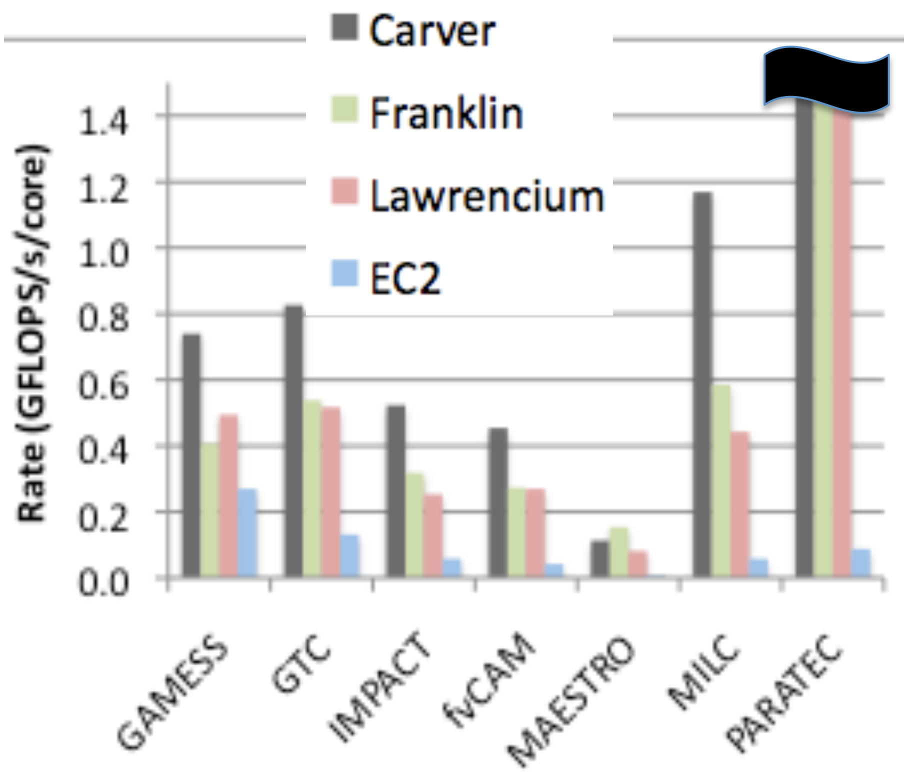
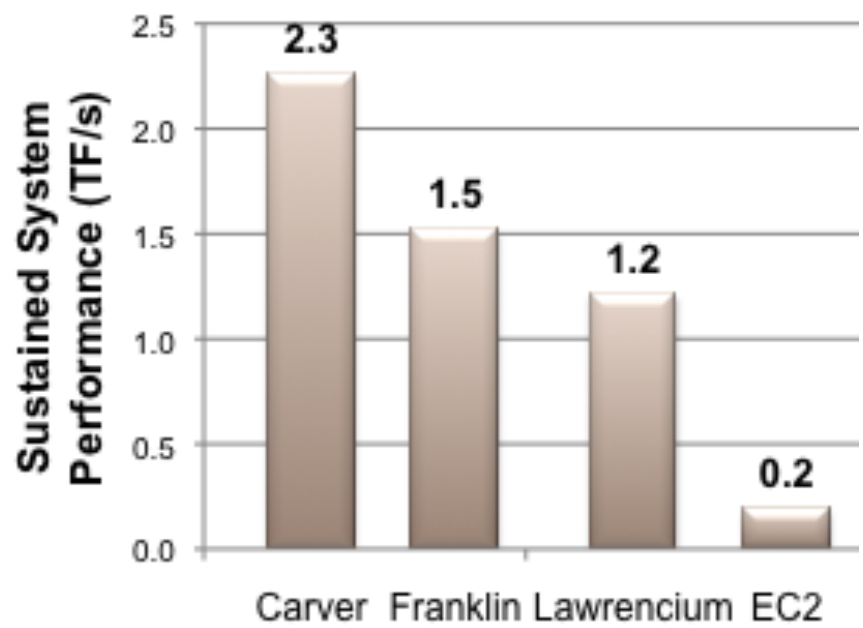
Application Rates and SSP





Carver: Infiniband Cluster
Franklin: Cray XT4 custom interconnect
Lawrencium: GigE cluster
EC2: high-instance (cloud)

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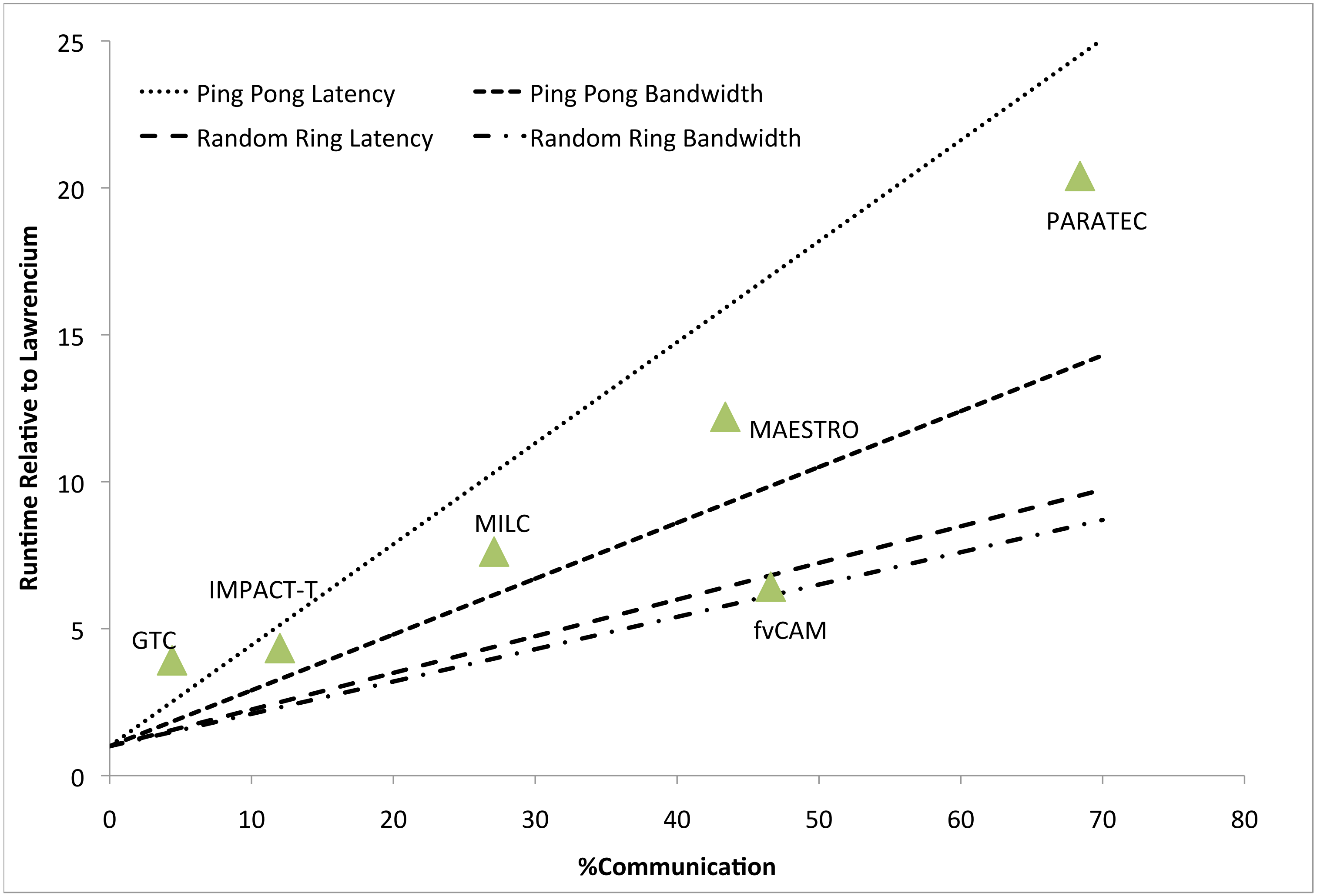
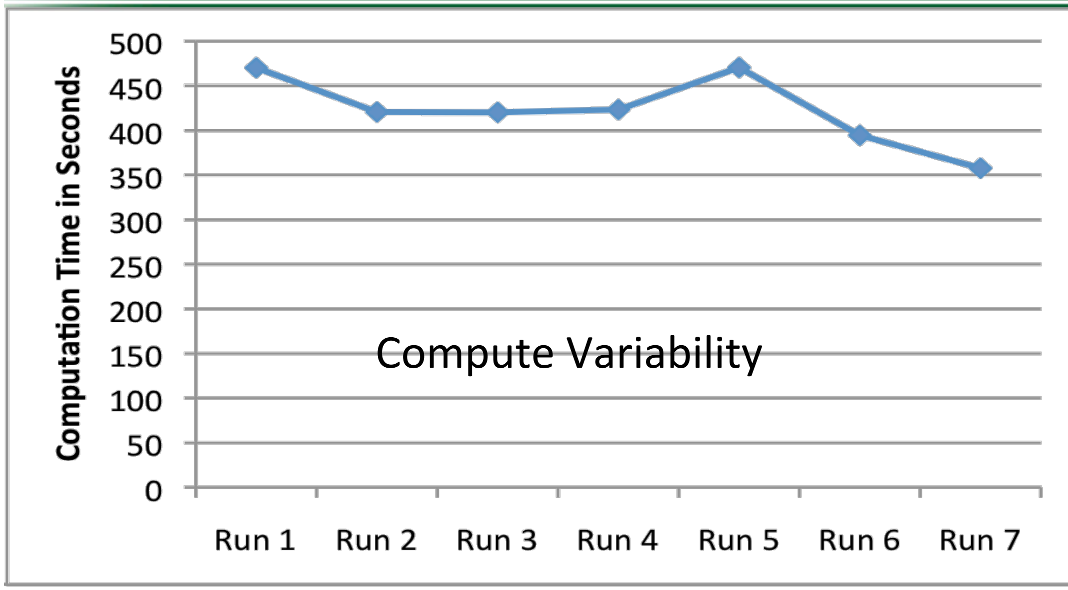
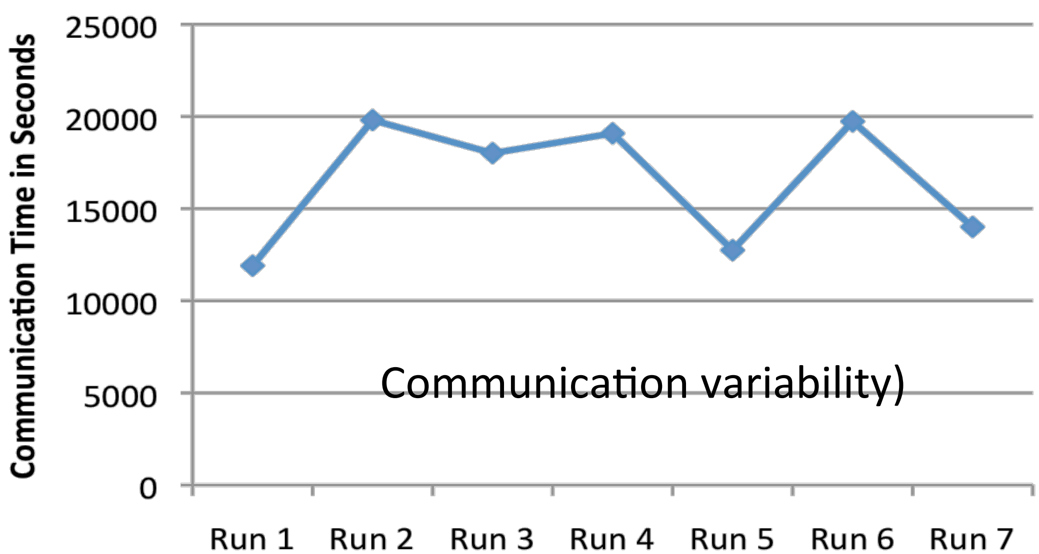
Correlation with Communication Performance



Variability (in compute and communication)



- **Modest variability in compute**
  - Not as bad ad communication, but substantially more than HPC systems
  - HPC codes not well structured to handle this variability



- **Lot of variability in communication performance**
  - Virtualization
  - Cross-traffic (contention)
  - Not topologically compact in cloud *(greedy scheduler puts things on different subnets*)

Overall Assessment in 2009

- **Significantly lower interconnect performance**
  - High overheads due to virtualization and TCP/IP overheads
  - Low effective bandwidth compared to IB or HPC-custom Nets.
- **Significant performance variability**
  - Stacking of VM's for spot-priced hardware
  - Expensive to use un-Virtualized (or non-stacked) hardware
  - Shared interconnect without placement affinity for instances (hotspots, contention, traffic interference)
- **Significantly higher MTBF:** Variety of transient failures, including
  - Boot failures and intermittent virtual machine hangs;
  - Inability to obtain requested resources.

- **Bottom Line**
  - Cost to operate HPC center $50M/year
  - Cost to operate equivalent Top500/Linpack system in cloud $200M/year
  - Cost to operate equivalent app. performance facility in cloud $1B/year

Cloud/Datacenter NEEDS high performance internal fabric *(requirements are starting to align with HPC)*

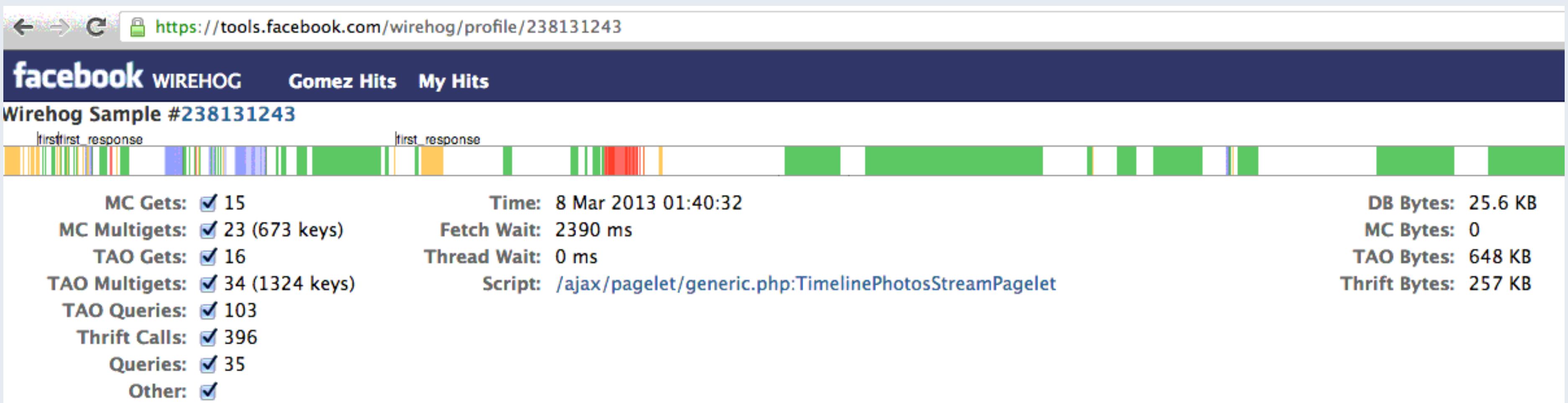
- **Old Hardware Drivers for Clouds**
  - **COTS: Lowest cost off-the-shelf Ethernet gear** (HPC pushed towards high-performance fabrics for best TCO.)
  - **External vs. Internal**: TCP/IP primarily to external network loads for web services (HPC primarily internally focused traffic patterns)
  - **Throughput vs. Overhead**: Throughput valued more than low latency + overheads (HPC needed lower latency)
  - **Overheads**: Stacked VMs for elasticity and dynamic loads (but hurt HPC due to performance heterogeneity and overheads)
  - **Contention**: Provision nodes for loosely coupled random traffic (tightly coupled jobs: provision contiguous topologies)
- **New Developments in Drivers for Cloud/Datacenter**
  - **Bikash Koley, Google Inc. (OI2012)**: **80%+** of Google traffic now internal facing *(used to be the other way around)*
  - **Dennis Abts, Google Inc. (2011 book):** High Performance Datacenter Networks: Architectures, Algorithms, and Opportunities
  - **Nathan Farrington, Facebook (OI2013)**: Every **1kb** of external traffic entering the datacenter generates **930kb** of internal traffic.

Facebook seeing huge internal traffic requirements

(Nathan Farrington, Facebook Inc., Presented at OIC2013)

HTTP request amplification

This 1 KB HTTP request generated 930 KB of internal network traffic



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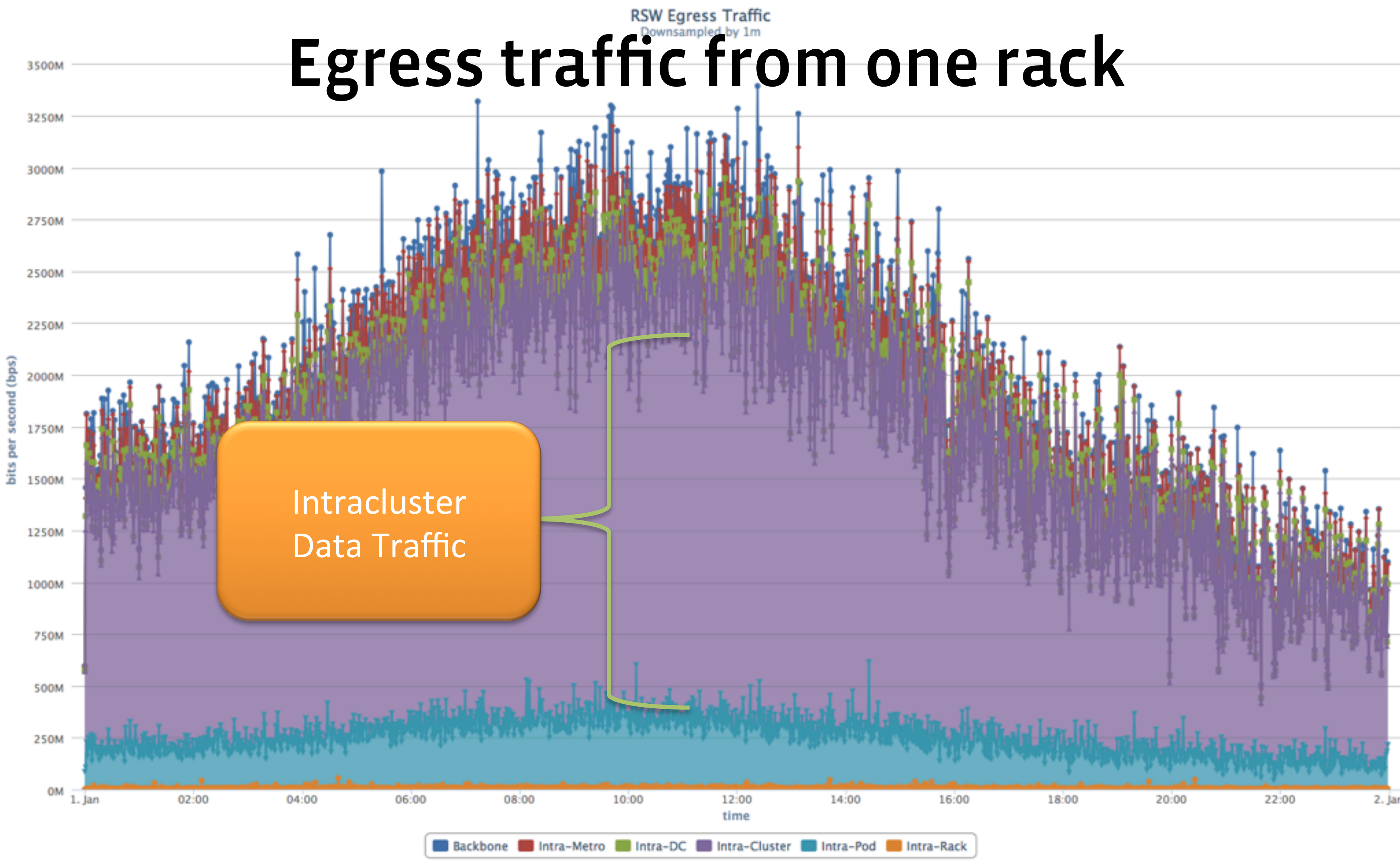
Majority of Facebook Traffic is Intra-Cluster

(Nathan Farrington, Facebook Inc., Presented at OIC2013)



New Requirements

- **New Requirements**
  - Need lower Overhead to send minimum sized messages
  - Higher intra-datacenter bandwidth

- **Cloud/Datacenter Responses**
  - Willing to sacrifice full TCP/IP stack (designed for wide area) to get higher performance and lower overheads inside of datacenters
  - Push towards hardware technology to reduce bandwidths and latencies
  - Push towards leaner more efficient software stacks

Google "Pluto Switch"

(fell off truck somewhere in Iowa)

OMG: Google is building its own semi-custom switches!

Responses to New Cloud/Datacenter Requirements

- **Custom Intra-Center Fabrics *(Google not waiting !!)***
  - Who the heck cares what you use for transport within the center?
  - Meaner/Leaner communications software stack
  - Modify switches to use more effective congestion control or avoidance
    - TCP/IP just uses inefficient lagging indicators of congestion or waits for packet drop + AIMD avoidance
  - Optical Circuit Switches: why use packet switching for persistent flows? *(e.g. OpenFlow, but make it a hard circuit for QoS guarantees)*

- **System on Chip (SOC): Move NIC into CPU chip (silicon motherboard)**
  - **Use Moore's law** to put more *peripherals* onto chip instead of more *cores*
  - **Reduces component count** *(reduces cost, size and complexity of motherboards)*
  - **Reduces power** (*fewer off-chip connections)*
  - **Reduces sources of failure** *(fewer solder joints and connectors… ask ORNL about that)*
  - **Increases performance** *(factor of 20x reduction in software overheads)*

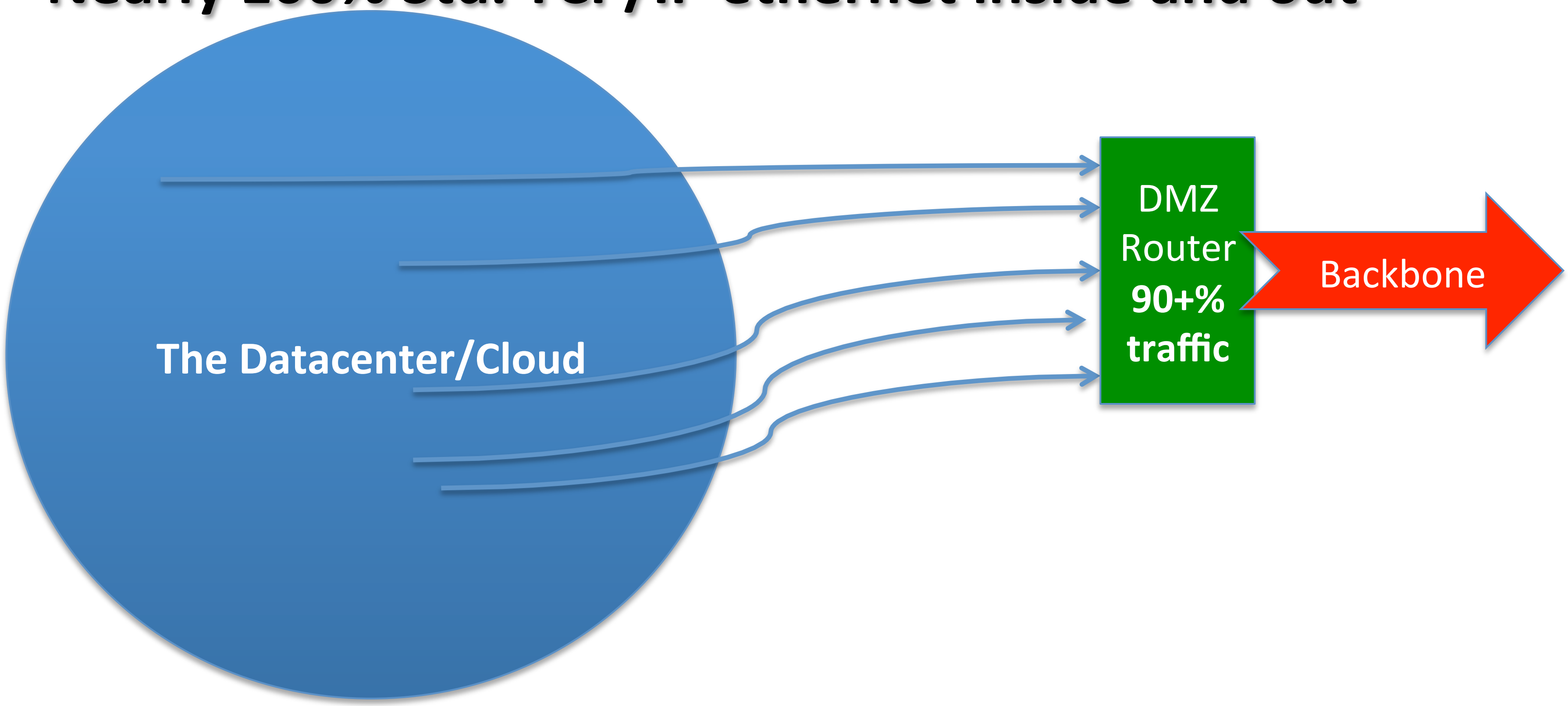
Response to the NEW Cloud/Datacenter Requirements

- **Intel Acquisition Spree**
  - **Qlogic**: Infiniband
  - **Fulcrum**: Ethernet
  - **Cray**: Aries (custom HPC)
  - **Quote from Raj Hazra** (to HPCwire 2012): **"We are seeing the role of the fabric far less like a network, in a loosely coupled sense, and far more like a system bus at the datacenter level**"
- **AMD Acquisitions**
  - **SeaMicro**: Atom + fabric to connect many together for datacenter

- **Ecosystem Disruption: We can no longer mix-n-match the processor with the interconnect *(CPU choice defines fabric)***
- **Bottom Line: If you are a CPU vendor who wants to play in the datacenters, need the NIC on the CPU chip**

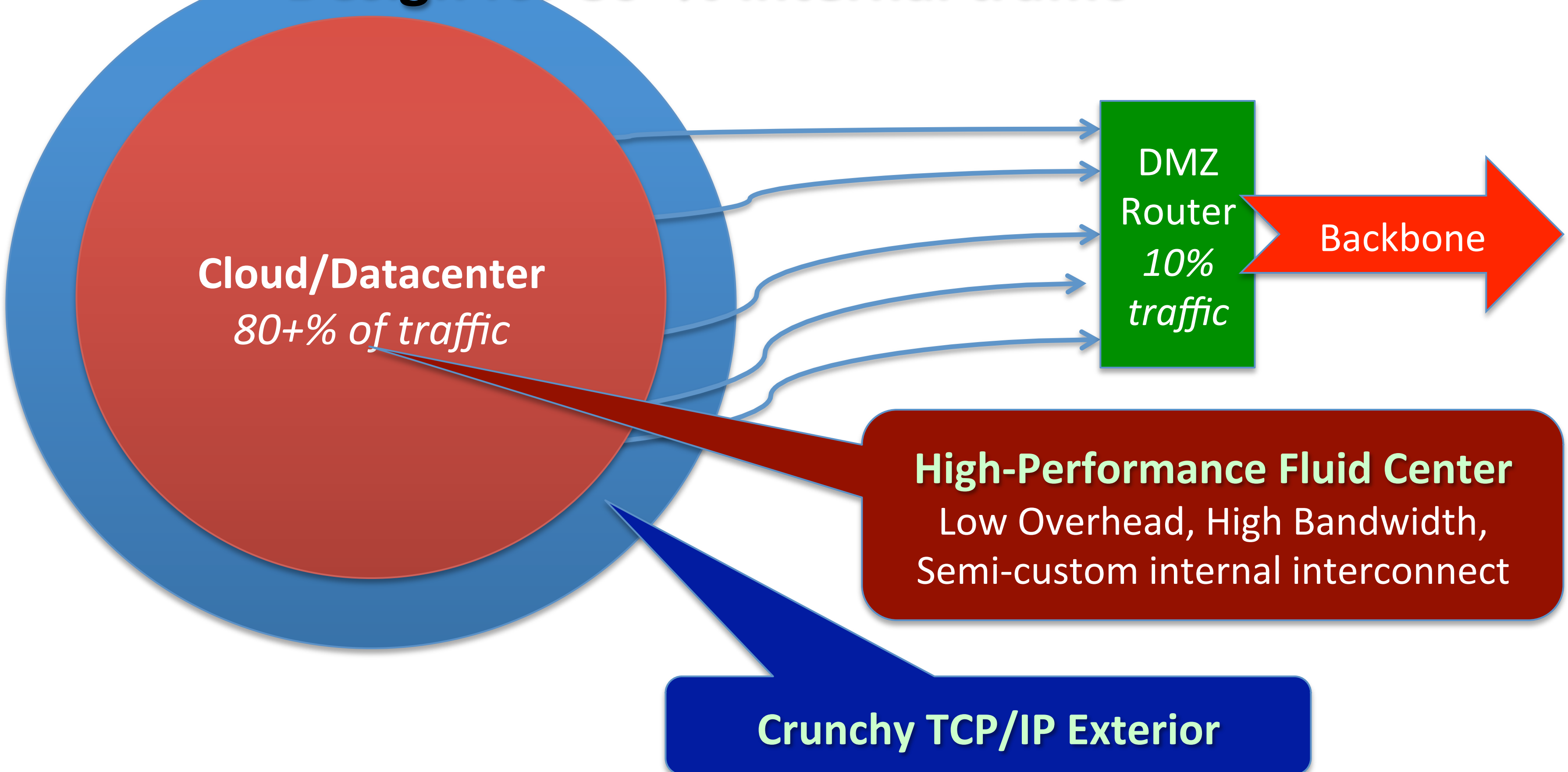
Old/New Conception of Cloud/Datacenters
(Simplified Conceptual Model)

Old Conception
Designed for externally facing TCP/IP
Nearly 100% Std. TCP/IP ethernet inside and out



Old/New Conception of Cloud/Datacenters
(Simplified Conceptual Model)

New Conception
Need to Handle Internal Data Mining/Processing
Design for 80+% internal traffic



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Looks Like Conceptual Diagram of a Typical HPC System

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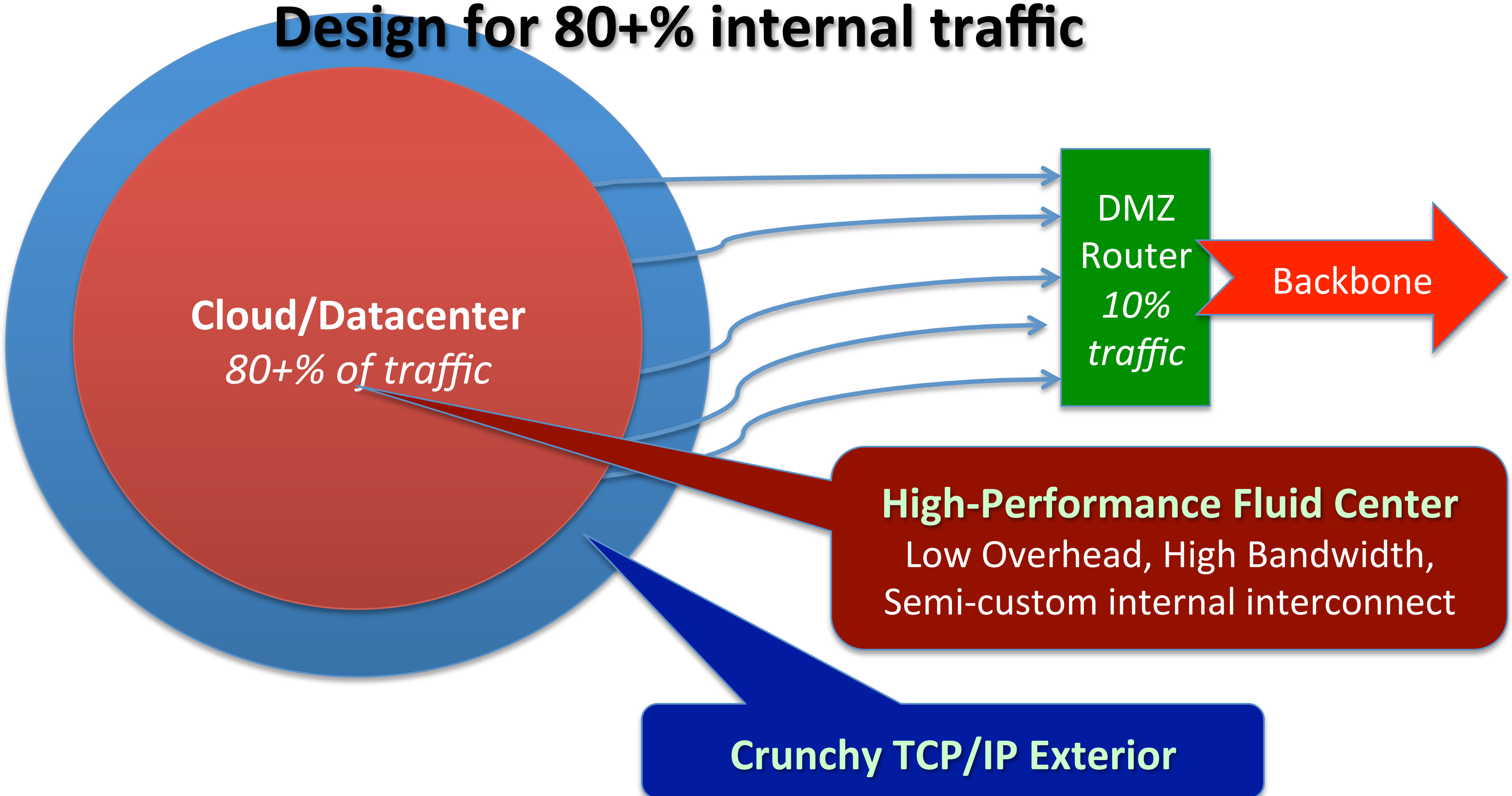


Convergence with HPC Requirements? (scorecard)

- ~~**COTS: Lowest cost off-the-shelf Ethernet gear** (HPC pushed towards high-performance fabrics for best TCO.)~~
- ~~**External vs. Internal**: TCP/IP primarily to external network loads for web services (HPC primarily internally focused traffic patterns)~~
- ~~**Throughput vs. Overhead**: Throughput valued more than low latency + overheads (HPC needed lower latency)~~
- ~~**Contention**: Provision nodes for loosely coupled random traffic (tightly coupled jobs: provision contiguous topologies)~~
- **Performance Variation**: Dynamic behavior for elasticity and cost (but hurt HPC due to performance heterogeneity and overheads)
- **Resilience**: Loosely coupled jobs, depend on software to tolerate failure (HPC tightly coupled parallelism depends on HW to avoid failures… software not very tolerant of faults)

Reformulating HPC Software to Tolerate Performance Variation and Failures

- **Today we have a bulk synchronous, distributed memory, communicating sequential processes (CSP) based execution model**
  - We've evolved into it over two decades
  - It will require a lot of work to carry it forward to exascale
  - The characteristics of today's execution model are mis-aligned with emerging hardware trends of the coming decade
- **Due Diligence to examine alternative execution models for HPC**
  - Alternatives exist, and they look promising *(e.g. async Ems such as SWARM, HPX, Charm)*
  - Use modeling and simulation to evaluate for DOE HPC applications
  - This can guide our hardware/software trade-offs in the codesign process, and expands options for creating more effective machines
- **Asynchronous EMs: *aligned with cloud/datacenter SW challenge***
  - Make software more tolerant of asynchrony than BulkSync/MPI
  - Make software more tolerant of failures than current approaches

Converging HPC Software with Cloud Hardware

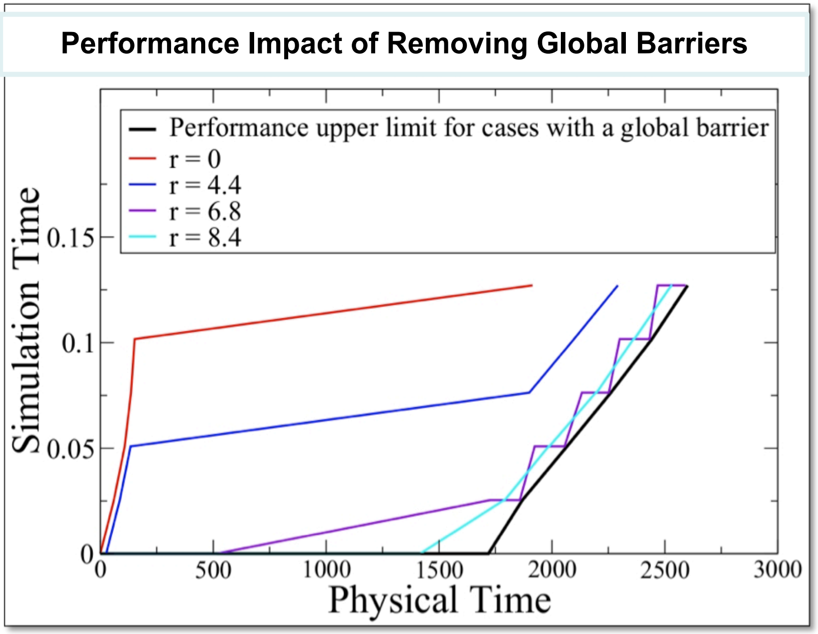
(meeting the cloud half-way)

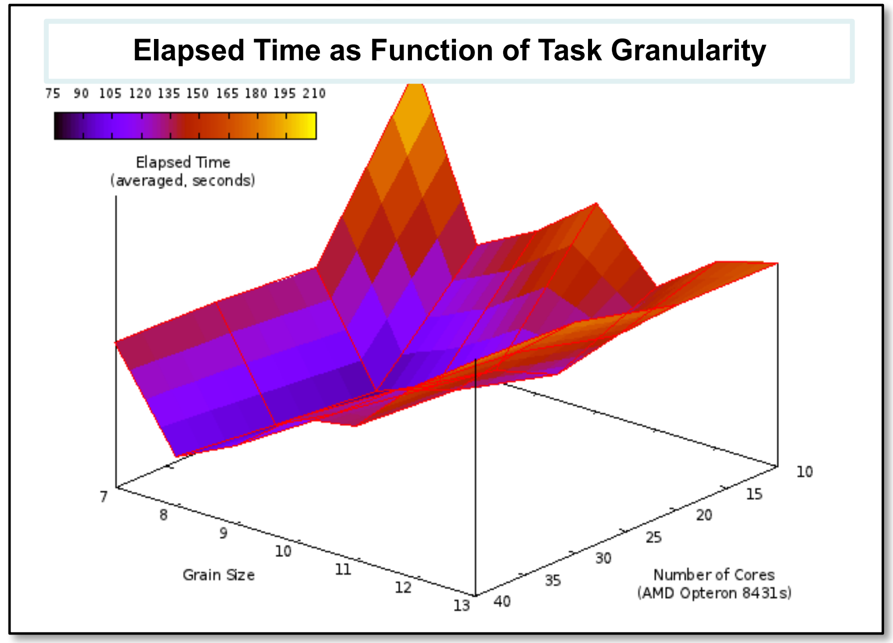
- **Meet the cloud half-way by redesigning to tolerate asynchrony and faults**

- **If successful would make cloud safe for HPC**
  - Enables more aggressive energy savings options
  - Side-benefit of overcoming the huge technical challenge of keeping 1B+ processors executing in lock-step, which sounds absurd on the face of it.

Rewrite of GTC to get Maximum Async Execution

(not a simple port of the application… need to reformulate the math)





- Eliminated Sources of Synchronization
- See ***some*** signs of async behavior/benefit (best task granularity > 7tasks/core
- But still suffer from barriers (still a long way to go to match “stupid mode”)

Issues

- Poisson solve creates implicit barrier (have to complete globally before moving on)
- Not just a CS exercise (don’t get to port to new library and call for success)
- Requires deep reformulation of the underlying math & algorithms to see benefits

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Preliminary Observations

- **We've spent 20 years rewriting Scientific numerical algorithms to eliminate non-bulk-sync behavior**
  - Its difficult to reverse such a global and comprehensive effort
  - It's a deep reformulation of the fundamental math/algorithm
  - It is NOT simply a matter of porting to the correct runtime/ communication system (or correct version of MPI3)

- **Potential benefits are substantial (so still working)**
  - Convergence with cloud/datacenter fabrics
  - Enables CPU vendors to pursue more aggressive power reduction strategies (NTV operation, fine-grained speed throttling, etc…)
  - Enable better approach to fault recovery

Conclusions for Hardware
(cloud datacenter hardware realignment)

- **Big data analytics pushing the cloud to high performance internal networking**
  - TCP/IP to outside world
  - High perf. custom nets or stripped down protocol internally

- **Server CPU vendors responding with Integrated NICs**
  - Natural consequence of SOC integration
  - Huge performance, cost and power benefits
  - Custom protocols to reduce CPU overheads

- **Implication: Hardware more aligned with HPC**

Conclusions for Software
(HPC software realignment)

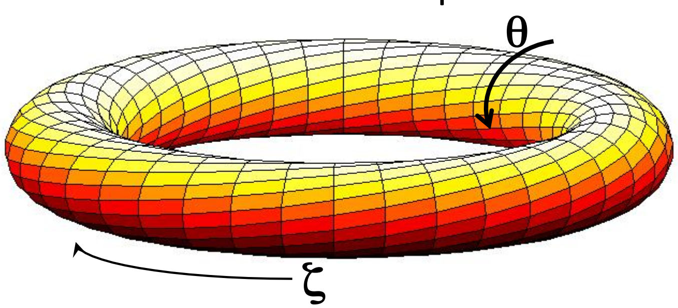
- **HPC hardware expected to be more heterogeneous and prone to faults**
  - Future requirements for HPC software more algined with what we consider deficiencies of today's cloud
  - Redesigning software to embrace solutions that overcome heterogeneity and resilience aligns with Cloud *and* exascale

- **But HPC software re-alignment is much deeper issue**
  - Not just choosing the correct communication library or langauge
  - Requires fundamental rethinking of algorithm and mathematics

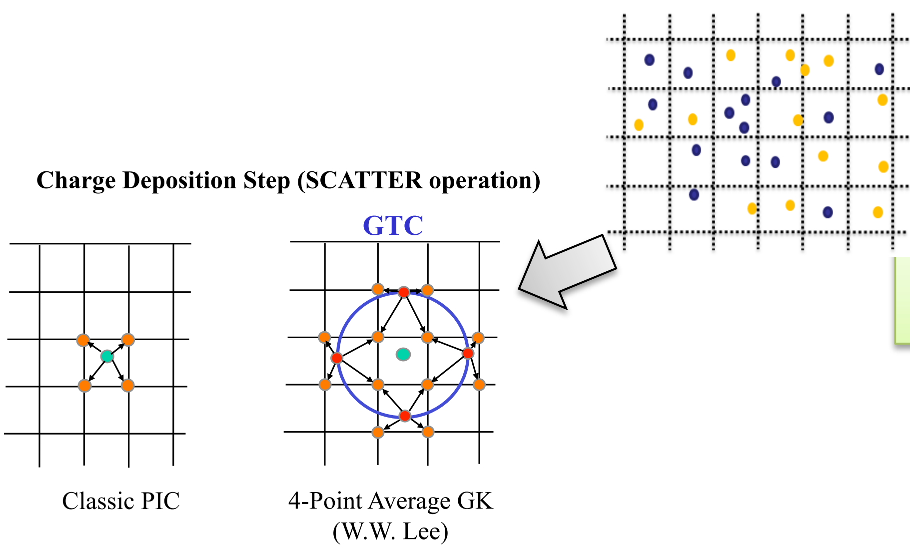
- **Implication: forcing function for HPC to push closer to clouds**

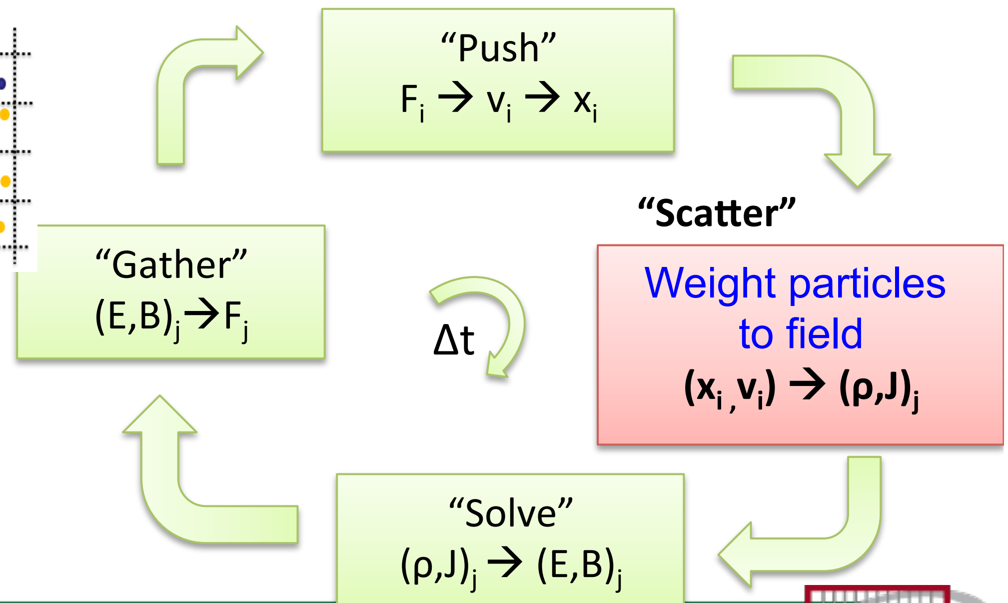
Starting with the Gyrokinetic Toroidal Code

- GTC uses PIC method to simulate plasma microturbulence for fusion devices
- Written in F90 with MPI
- Scalable to thousands of processors

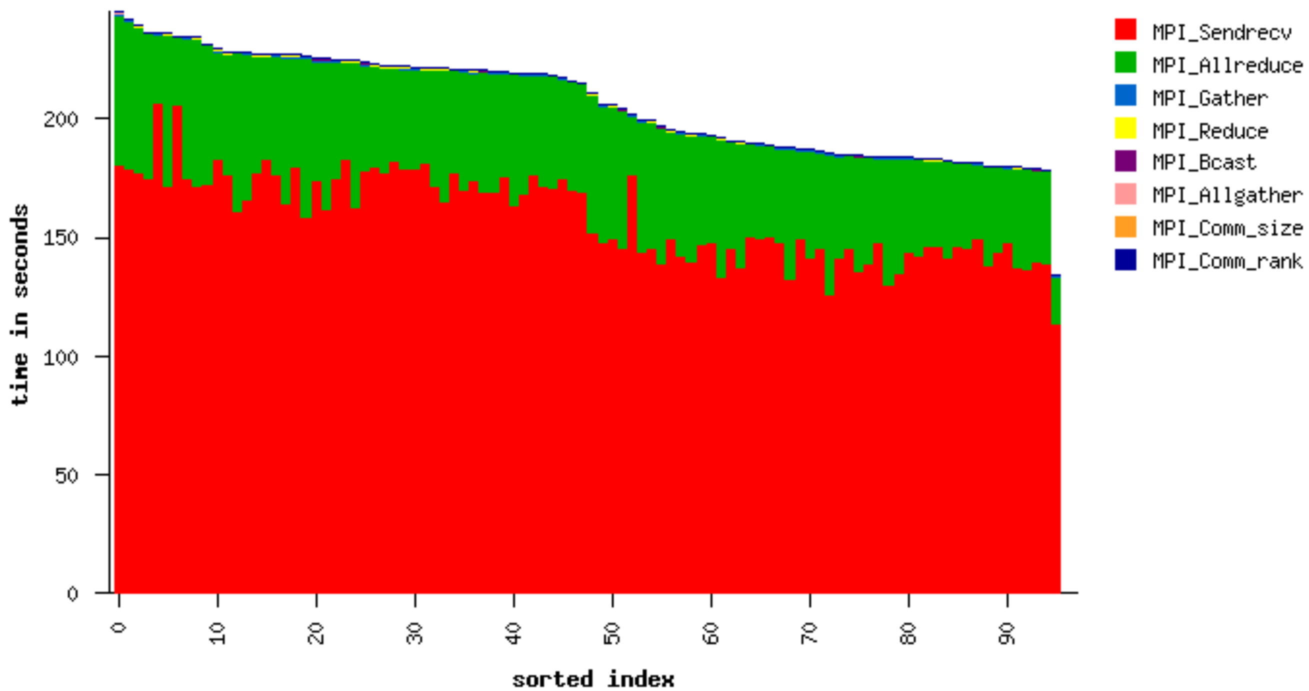


- Grid memory accesses depend on the order in which particles are processed.
- In a multithreaded implementation with a shared grid, multiple threads update grid locations in parallel.
- The case of random particle positions and parallel updates is similar to the GUPS benchmark. However, implementations usually exploit the fact that PIC is a physical many-body simulation method.





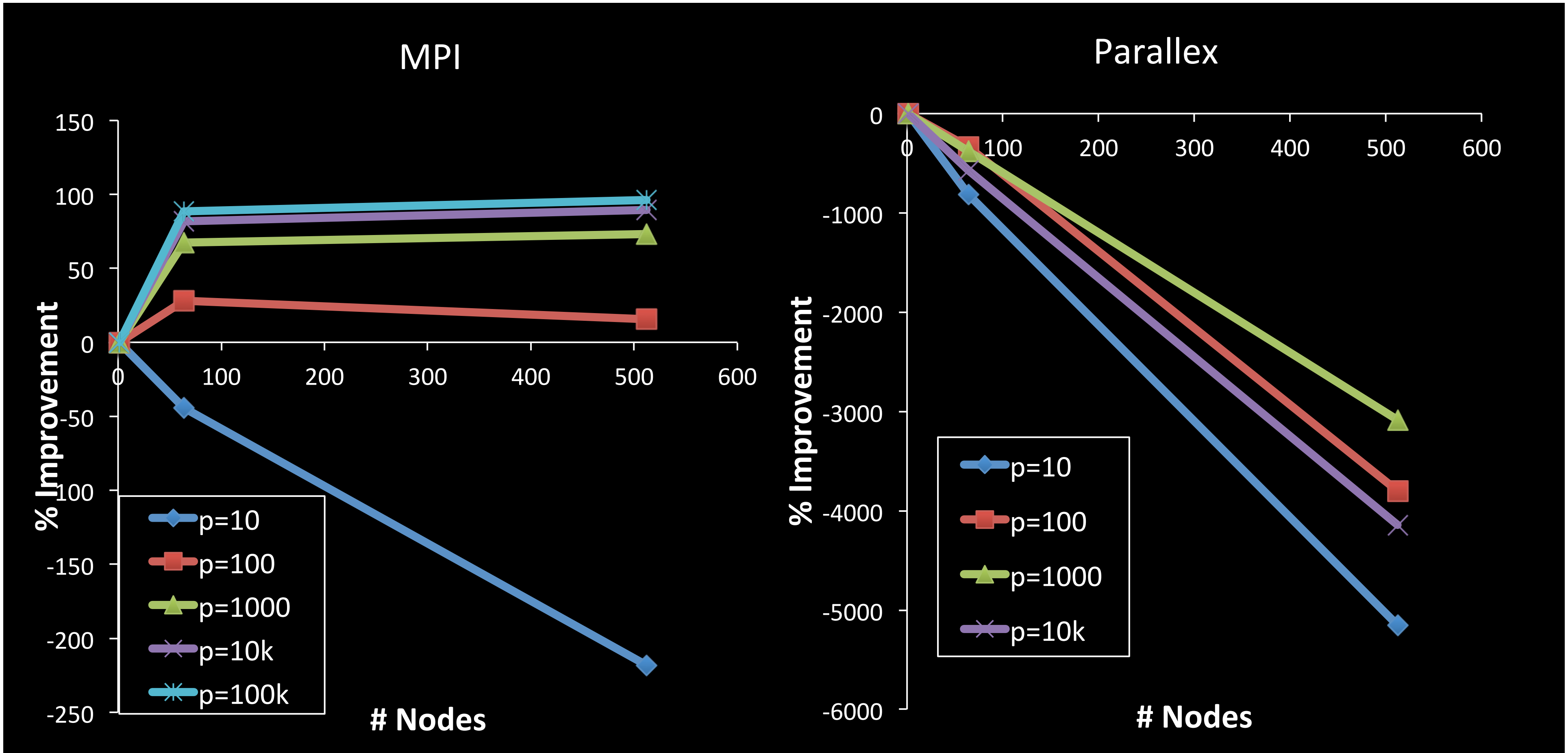
GTC: Load Imbalance



- **Typical load imbalance performance loss can be between 10-30% of the runtime, depending on concurrency and problem definition**
- **Partially due to:**
  - Dynamic nature of the computation- different numbers of particles move at each time step
  - Initial conditions – static load-imbalance

Initial Scaling Results Disappointing
(can't port directly from MPI to Async)

- \- How does a fixed problem scale with machine size (strong scaling), oversubscription = 2



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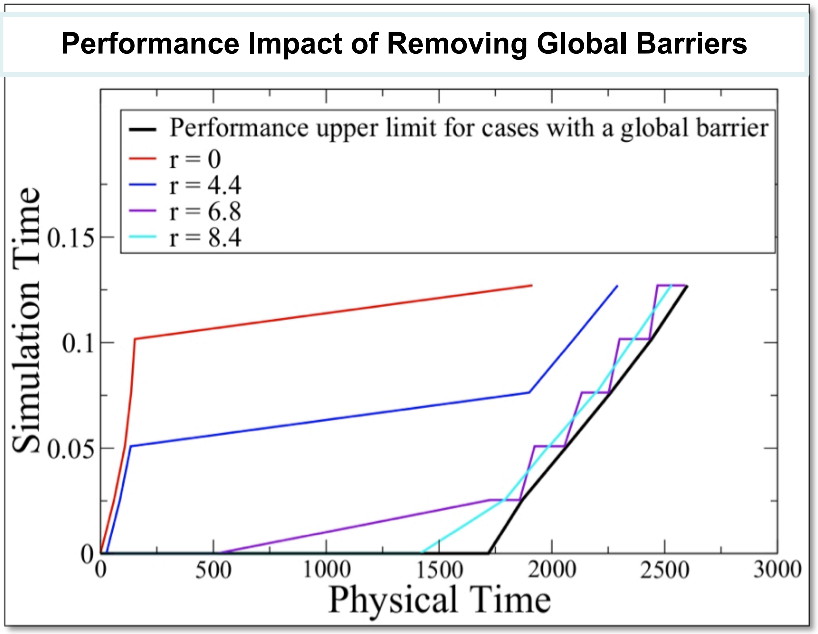

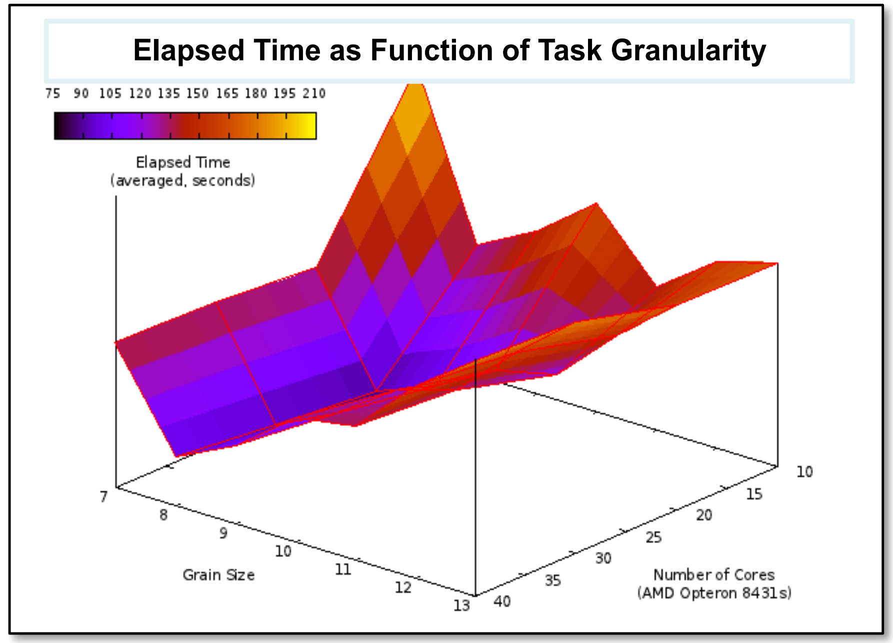

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Summary of HPC Clouds 2009

- **Weaknesses of Cloud/Datacenter Technology for HPC**
  - Ethernet inhibits MPI communication performance
  - Performance inconsistency due to virtualization and fabric loading hurts synchronous apps
  - Significantly greater performance range
  - Failure rates high for application benchmarks

- **Building Clouds for Science**
  - Use high-performance fabric (IB)
  - Shared global filesystem
  - Don't stack VM images (or offer un-virtual access to hardware)
  - Improved fault resilience, or improved application resilience

- **Not measured: I/O and network performance**

Some other things for Clouds/Datacenters to Consider

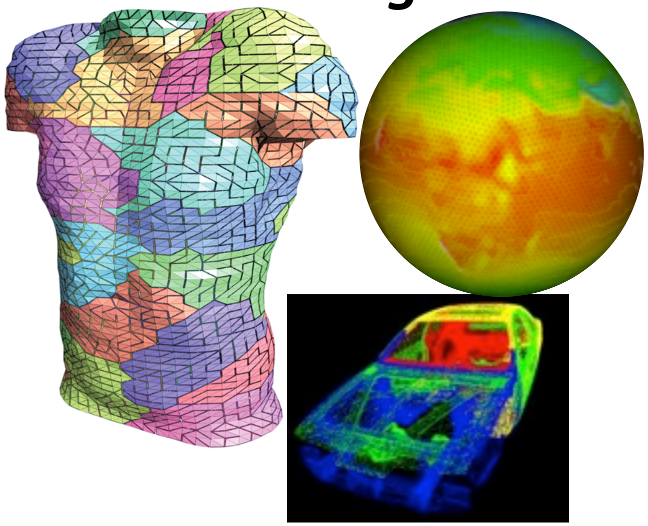
- **Lightweight communication libraries**
  - Already seeing benefits of paring down TCP/IP protocol
  - Additional benefits realized from considering alternative APIs e.g. GAS

- **UPC or PGAS for data mining**
  - GAS is really good for irregular graph problems
  - NSA has been at this for a long time
  - Might have something to learn (although they won't tell you)

- **Data locality/topology awareness**
  - Naïve random all-to-all is just bisection bandwidth buster (not much freedom for innovation in hardware or software)
  - Data movement distance is huge power cost (see Dally talk!)
  - If there is any exploitable locality, take advantage of it (understand that Google's internal replacement for MapReduce does just that)

UPC Was Designed for Irregular Data-Mining Problems

More Regular



__**Message Passing Programming**__

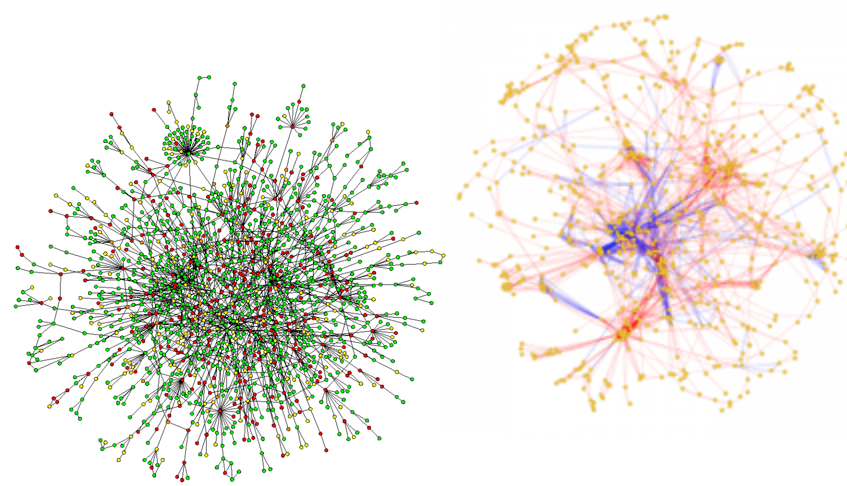
Divide up domain in pieces

Compute one piece

Send/Receive data from others

MPI, and many libraries

More Irregular



__**Global Address Space Programming**__

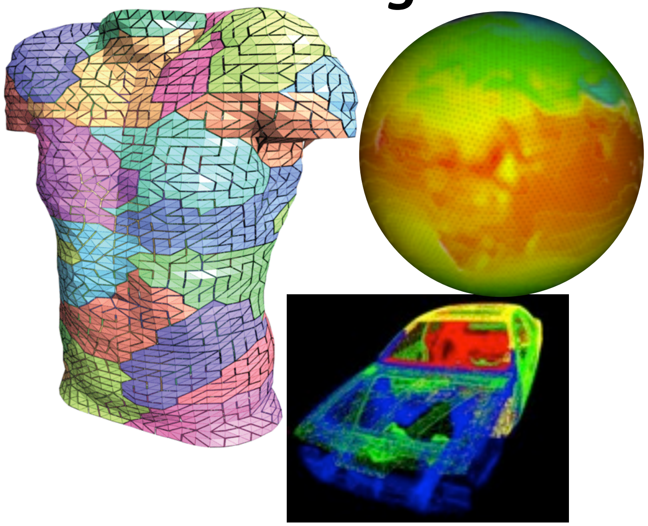
Each start computing

Grab whatever / whenever

UPC, CAF, X10, Chapel, GlobalArrays

UPC Designed for Irregular "big data" Problems
(plug to support HPC features like GAS in fabric)

More Regular



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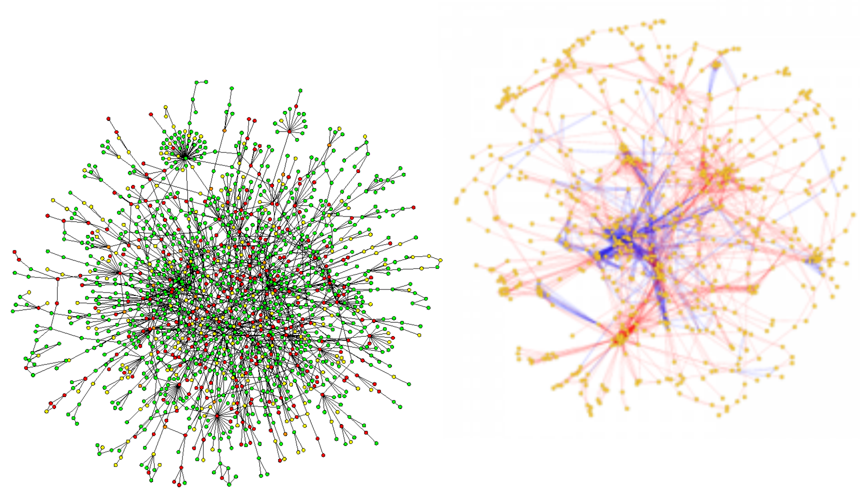

<u>Global Address Space Programming</u>

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(NSA has been in big-data biz with UPC for long time)