The Exascale Challenge:

How Technology Disruptions Fundamentally Change Programming Systems

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High End Modeling and Data Assimilation For Advanced Combustion Research

Approach: Combine unique codes and resources to maximize benefits of high performance computing for turbulent combustion research

Advanced “capability-class” solvers

Access to leading edge computational resources

DNS to investigate combustion phenomena at smallest scales

no modeling
limited applicability

LES to investigate coupling over full range of scales in experiments

minimal modeling
full geometries

CRF Computational Combustion and Chemistry Laboratory
Combustion Research and Computational Visualization Facility

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DOE Office of Science Laboratories
LBNL NERSC
ORNL OLCF
ANL ALCF
INCITE Program

Ofelein, Chen: Sandia 2009
Combustion Research has demonstrated a long history of scientific breakthroughs resulting from joint advances in Algorithms, Applications, and HPC Capability.

*Need for more simulation fidelity drives insatiable need for larger scale systems.*
Two Decades of Exponential Performance Improvements

Source: TOP500 November 2012
Computing Crisis is Not Just about Exascale

Microprocessor Performance “Expectation Gap (1985-2020 projected)

Industry motivated, path forward is unclear
Technology Challenges for the Next Decade

Power is leading constraint for future performance growth

Parallelism is growing at exponential rate

Reliability going down for large-scale systems, but also to get more energy efficiency for small systems

Memory Technology improvements are slowing down

By 2018, cost of a FLOP will be less than cost of moving 5mm across the chip’s surface (locality will really matter)
Whats wrong with current HPC Systems?  
Designed for Constraints from 30 years ago! (wrong target!!)

## Old Constraints

- **Peak clock frequency** as primary limiter for performance improvement
- **Cost**: FLOPs are biggest cost for system: optimize for compute
- **Concurrency**: Modest growth of parallelism by adding nodes
- **Memory scaling**: maintain byte per flop capacity and bandwidth
- **Locality**: MPI+X model (uniform costs within node & between nodes)
- **Uniformity**: Assume uniform system performance
- **Reliability**: It's the hardware’s problem

## New Constraints

- **Power** is primary design constraint for future HPC system design
- **Cost**: Data movement dominates: optimize to minimize data movement
- **Concurrency**: Exponential growth of parallelism within chips
- **Memory Scaling**: Compute growing 2x faster than capacity or bandwidth
- **Locality**: must reason about data locality and possibly topology
- **Heterogeneity**: Architectural and performance non-uniformity increase
- **Reliability**: Cannot count on hardware protection alone

Fundamentally breaks our current programming paradigm and computing ecosystem
Programming Models are a Reflection of the Underlying Machine Architecture

- *Express what is important for performance*
- *Hide complexity that is not consequential to performance*

Programming Models are Increasingly Mismatched with Underlying Hardware Architecture

- *Changes in computer architecture trends/costs*
- *Performance and programmability consequences*

Technology changes have deep and pervasive effect on ALL of our software systems *(and how we program them)*

- *Change in costs for underlying system affect what we expose*
- *What to virtualize*
- *What to make more expressive/visible*
- *What to ignore*
The Programming Model is a Reflection of the Underlying *Abstract Machine Model*

**Equal cost SMP/PRAM model**
- No notion of non-local access
- \( \text{int } [nx][ny][nz] \);

**Cluster: Distributed memory model**
- No unified memory
- \( \text{int } [\text{localNX}][\text{localNY}][\text{localNZ}] \);

**PGAS for horizontal locality**
- Data is LOCAL or REMOTE
- shared [Horizontal] \( \text{int } [nx][ny][nz] \);

**Whats Next?**
Parameterized Machine Model
(what do we need to reason about when designing a new code?)

Cores
- How Many
- Heterogeneous
- SIMD Width

Network on Chip (NoC)
- Are they equidistant or
- Constrained Topology (2D)

On-Chip Memory Hierarchy
- Automatic or Scratchpad?
- Memory coherency method?

Node Topology
- NUMA or Flat?
- Topology may be important
- Or perhaps just distance

Memory
- Nonvolatile / multi-tiered?
- Intelligence in memory (or not)

Fault Model for Node
- FIT rates, Kinds of faults
- Granularity of faults/recovery

Interconnect
- Bandwidth/Latency/Overhead
- Topology

Primitives for data movement/sync
- Global Address Space or messaging?
- Synchronization primitives/Fences
For each parameterized machine attribute, can

- **Ignore it:** *If ignoring it has no serious power/performance consequences*
- **Expose it** (**unvirtualize**): *If there is not a clear automated way of make decisions*
  - Must involve the human/programmer in the process (**make pmodel more expressive**)
  - Directives to control data movement or layout (for example)
- **Abstract it** (**virtualize**): *If it is well enough understood to support an automated mechanism to optimize layout or schedule*
  - This makes programmers life easier (one less thing to worry about)

**Want model to be as simple as possible, but not neglect any aspects of the machine that are important for performance**
The Problem with Wires:

Energy to move data proportional to distance

- Cost to move a bit on copper wire:
  - energy = bitrate * Length^2 / cross-section area

- Wire data capacity constant as feature size shrinks
- Cost to move bit proportional to distance
- ~1TByte/sec max feasible off-chip BW (10GHz/pin)
- Photonics reduces distance-dependence of bandwidth

Photonics requires no redrive and passive switch little power

Copper requires to signal amplification even for on-chip connections
Cost of Data Movement Increasing Relative toOps

- FLOPs will cost less than on-chip data movement! (NUMA)
If FLOPS are free, then why do we need an “exaflops” initiative?

“Exa”-anything has become a bad brand
• Associated with buying big machines for the labs
• Associated with “old” HPC
• Sets up the community for “failure”, if “goal” can’t be met
Data Locality Management

**Vertical Locality Management**
*spatio-temporal optimization*

**Horizontal Locality Management**
*topology optimization*
Current Practices (2-level Parallelism)
NUMA Effects Ignored (with huge consequence)

MPI+OMP Hybrid

- Reduces memory footprint
- Increases performance up to NUMA-node limit
- *Then programmer responsible for matching up computation with data layout!! (UGH!)*
- Makes library writing difficult and *Makes AMR nearly impossible!*

It’s the Revenge of the SGI Origin2000

Bad News!
Expressing Hierarchical Layout

Old Model (OpenMP)
- Describe how to parallelize loop iterations
- Parallel “DO” divides loop iterations evenly among processors
- (but where is the data located?)

New Model (Data-Centric)
- Describe how data is laid out in memory
- Loop statements operate on data where it is located
- Similar to MapReduce, but need more sophisticated descriptions of data layout for scientific codes

```
upc_forall (i=0;i<NX;i++;A)
```
Data-Centric Programming Model
(current compute-centric models are mismatched with emerging hardware)

Building up a hierarchical layout

Layout block coreblk \{blockx,blocky\};
Layout block nodeblk \{nnx,nny,nnz\};
  • Layout hierarchy myheirarchy \{coreblk,nodeblk\};
  • Shared myhierarchy double a[nx][ny][nz];

• Then use data-localized parallel loop
  \texttt{doall\_at}(i=0;i<nx;i++;a)\
    \texttt{doall\_at}(j=0;j<ny;j++;a)\
    \texttt{doall\_at}(k=0;k<nz;k++;a)\
    a[i][j][k]=C*a[i+1]…>

• And if layout changes, this loop remains the same

Satisfies the request of the application developers
(minimize the amount of code that changes)
Heterogeneity / Inhomogeneity
Async Programming Models?
Assumptions of Uniformity is Breaking (many new sources of heterogeneity)

Bulk Synchronous Execution

- Heterogeneous compute engines (hybrid/GPU computing)
- Fine grained power mgmt. makes homogeneous cores look heterogeneous
  - thermal throttling – no longer guarantee deterministic clock rate
- Nonuniformities in process technology creates non-uniform operating characteristics for cores on a CMP
  - Near Threshold Voltage (NTV)
- Fault resilience introduces inhomogeneity in execution rates
  - error correction is not instantaneous
  - And this will get WAY worse if we move towards software-based resilience
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Bulk Synchronous Execution

Asynchronous Execution Model
Conclusions on Heterogeneity

Sources of performance heterogeneity increasing
• Heterogeneous architectures (accelerator)
• Thermal throttling
• Performance heterogeneity due to transient error recovery

Current Bulk Synchronous Model not up to task
• Current focus is on removing sources of performance variation (jitter), is increasingly impractical
• Huge costs in power/complexity/performance to extend the life of a purely bulk synchronous model

Embrace performance heterogeneity: Study use of asynchronous computational models (e.g. SWARM, HPX, and other concepts from 1980s)
Emerging hardware constraints are increasingly mismatched with our current programming paradigm

• Current emphasis is on preserving FLOPs
• The real costs now are not FLOPs… it is data movement
• Requires shift to a data-locality centric programming paradigm and hardware features to support it

Technology Changes Fundamentally Disrupt our Programming Environment

• The programming environment and associated “abstract machine model” is a reflection of the underlying machine architecture
• Therefore, design decisions can have deep effect your entire programming paradigm
• Hardware/Software Codesign MUST consider ergonomic decisions about your programming environment together with performance

Performance Portability Should be Top-Tier Metric for CoDesign process

• Know what to IGNORE, what to ABSTRACT, and what to make more EXPRESSIVE