Green Flash: Designing Energy Efficient Computers for Cloud System Resolving Climate Models and Other Exascale Applications

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“…exascale computing will revolutionize our approaches to global challenges in energy, environmental sustainability, and security.”

*Simulation & Modeling at the Exascale for Energy & the Environment*  
– DOE E3 report
Global Cloud System Resolving Climate Modeling

- Individual cloud physics fairly well understood
- Parameterization of mesoscale cloud statistics performs poorly.
- Direct simulation of cloud systems in global models requires exascale!

- Direct simulation of cloud systems replacing statistical parameterization.
  - This approach recently was called for by the 1st WMO Modeling Summit.

- Championed by Prof. Dave Randall, Colorado State University
Global Cloud System Resolving Models are a Transformational Change

Surface Altitude (feet)

200km
Typical resolution of IPCC AR4 models

25km
Upper limit of climate models with cloud parameterizations

1km
Cloud system resolving models
How expensive is a GCSRM?

- GCSRM: Global Cloud System Resolving Model
  - A complete one does not actually exist...

- Build a model to quantify code requirements by measuring and extrapolating the parts

- Four parts for the atmospheric model:
  - Dynamics
  - Fast physics (cloud processes and turbulence)
  - Slow physics (radiation transport)
  - MultiGrid solver (elliptic equation solution)

- Code requirements model will predict necessary flops, memory, communication, memory i/o to achieve the throughput goals.
  - Target is to simulate time 1000 times faster than real time.
CSU atmospheric model

• Target resolution is 167,772,162 vertices, ~128 vertical levels, ~1.75 km
Code Requirements Model

• Measure and extrapolate:
  – Operation count
  – Main memory footprint
  – Cache memory footprint (local store, not cache coherent)
  – Memory bandwidth (bytes/flop)
  – Instruction mix
  – Interconnect bandwidth
  – Interconnect latency
  – Interconnect topology

• Derived constraints
  – Power (core + memory+interconnect)
  – Pins (memory + interconnect)
  – Mix of instruction in hardware (Flops, integer ops, branch, etc)
CSU atmospheric model

• 167,772,162 vertices, ~128 vertical levels, ~1.75 km
  – A truly transformational change to climate change modeling
  – 12.6+ Pflops sustained (for 1000x speedup)
  – 560TB total memory

• Ensembles of simulations (~10) → 100 Pflops sustained

• Climate codes typically run at 5% of peak or less

2 Exaflops
(or its equivalent)
New Constraints

- 15 years of *exponential* clock rate growth has ended

Moore’s Law reinterpreted:

- How to leverage transistors to increase performance at historical rates?
- Power is the new design constraint.
  - Nonlinear: CPU speed & size
- Multicore: # cores double 18-24 months.

Accelerating supercomputing demand:

- End of straightforward serial improvements
- Much higher parallelism will be required to exploit this technology

Figure courtesy of Kunle Olukotun, Lance Hammond, Herb Sutter, and Burton Smith
Exaflops will be hard!
… and the power costs will still be staggering

From Peter Kogge, DARPA Exascale Study
The Challenge

• How to get to this level of performance without an annual electric bill greater than today’s procurement costs?
• How do you achieve this in a decade with a finite development budget?
Green Flash: Overview

We present an alternative approach to developing systems to serve the needs of scientific computing

- Choose our science target first to drive design decisions
- Leverage new technologies driven by consumer market
- **Auto-tune software** for performance, productivity, and portability
- Use hardware-accelerated architectural emulation to rapidly prototype designs (**auto-tune the hardware too!**)

- **A holistic approach:** innovate algorithm/software/hardware together (Co-tuning)

Achieve 100x energy efficiency improvement over mainstream HPC approach
The portable consumer electronics market:

- Optimized for low power, low cost, and high computational efficiency

“Years of research in low-power embedded computing have shown only one design technique to reduce power: reduce waste.”

—Mark Horowitz, Stanford University & Rambus Inc.

Sources of Waste:

- Wasted transistors (surface area)
- Wasted computation (useless work/speculation/stalls)
- Wasted bandwidth (data movement)
Consumer Electronics has Replaced PCs as the Dominant Market Force in CPU Design

Netbooks based on Intel Atom embedded processor is the fastest growing portion of "laptop" market.

From Tsugio Makimoto: ISC2006
History repeats itself

1990s – HPC made the transition from vector to highly parallel platforms
  • Had to learn how to use desktop COTS technology for scientific computing

Now- R&D investments moving to consumer electronics/embedded processing
  • Must learn to leverage embedded technology for future HPC systems

Tsugio Makimoto ISC2006
Design for Low Power: More Concurrency

IBM Power5 (server)
- 120W@1900MHz

Cubic power improvement with lower clock rate due to V²F
- Intel Core2 sc (laptop)
  15W@1000MHz

Slower clock rates enable use of simpler cores – shorter pipelines, less area, lower leakage
- IBM PPC 450 (BG/P - low power)
  3W@800MHz

Tailor design to application to reduce waste
- Tensilica XTensa (Moto Razor)
  0.09W@600MHz
Low Power Design Principles

Even if each core operates at 1/3 of the frequency of fastest available processors, you can pack 100s of simple cores onto a chip and consume 1/10 the power.

One IBM Power5
- 120W
- 1900MHz

128 Tensilica Xtensa DP
- 11.5W
- equivalent to 76,800MHz

If the application has enough parallelism the many-core chip can be much faster and consume less power.
CS101: How to design a power efficient computer

• Spec out the requirements of your code.
  – Aim for a class of codes, not just one

• Learn how to design processors and interconnects.
  – We obtained chip design tools from Tensilica, a leading designer of chips for cell phones and other consumer electronics.
    • Each chip design comes with its own C compiler and debugger

• Emulate your chip design on your code.
  – RAMP emulates chips with FPGAs
    • Hardware emulation is more accurate and thousands of times faster than software emulation

• Iterate your chip design and your software.
  – Autotuning takes advantage of the specific C compiler
  – Profile the code to determine chip parameters.
Embedded Design Automation
(Example from Existing Tensilica Design Flow)

Leverage mainstream tools, design processes, and commodity IP. Allows potential for HW/SW co-design

Processor configuration
1. Select from menu
2. Automatic instruction discovery
3. Explicit instruction description

Processor Generator (Tensilica)

Application-optimized processor implementation (RTL/Verilog)

Tailored SW Tools: Compiler, debugger, simulators, Linux, other OS Ports
Derived HW characteristics: size, power, etc.

Build with any process in any fab
Or emulate performance prior to fab
Advanced Hardware Simulation (RAMP)

Research Accelerator for Multi-Processors (RAMP)

- Utilize FGPA boards to emulate multicore systems
- 1000x speedup versus software emulation
- Allows fast performance validation
- Emulates entire application (not just kernel)
- Break slow feedback loop for system designs
- Enables tightly coupled hardware/software/science co-design

Technology partners:

- UC Berkeley: John Wawrzynek, Jim Demmel, Krste Asanovic, Kurt Keutzer
- Stanford/ Rambus Inc.: Mark Horowitz
- Tensilica Inc.: Chris Rowen
Demonstration of Green Flash Approach

**SC ’09 Demo** of approach feasibility
- CSU limited-area atmospheric model ported to Tensilica architecture
- Dual-core Tensilica processor running atmospheric model
- Eight and Sixteen Core configuration coming online
- MPI Routines ported to custom interconnect

**Emulation performance advantage**
- Processor running at 25MHz vs. Functional model at 100 kHz (250x speedup)

*Actual code running - not representative benchmark*
Auto-Tuning for Green Flash

Challenge: How to optimize the climate code for the differing chip designs under consideration.

Solution: Auto-tuning

- Different chip designs may require vastly different optimizations
- Labor-intensive
- Automate search across a complex optimization space

“Never send a human to do a machine's job.”
– Agent Smith, The Matrix
Autotuning Example

• Operators extracted from climate code before and after auto-tuning

do k=0,km,1
do iprime=1,nside,1
do i=2,im2nghost-1,1
   ia = i + ii(iprime)
do j=2,jm2nghost-1,1
   ja = j + jj(iprime)
   buoyancy_gen(i,j,iprime,k) = -1.0 * g * (theta(ia,ja,k) - theta(i,j,k)) / theta00(k) * el(iprime)
endo
do iprime=1,nside,1
do i=2,im2nghost-1,1
   ia = i + ii(iprime)
do j=2,jm2nghost-1,1
   ja = j + jj(iprime)
   buoyancy_gen(i,j,iprime,k) = -1.0 * g * (theta(ia,ja,k) - theta(i,j,k)) / theta00(k) * el(iprime)
endo
do k=0,km,4
do G14906=0,km,4
do G14907=1,nside,6
do G14908=2,im2nghost - 1,25
do G14909=2,jm2nghost - 1,25
do k=G14906,G14906 + 1,1
do iprime=G14907,G14907 + 5,1
do i=G14908,G14908 + 24,1
   ia = i + ii(iprime)
do j=G14909,G14909 + 24,1
   ja = j + jj(iprime)
   buoyancy_gen(i,j,iprime,k) = -1.0 * g * theta(ia,ja,k) - theta(i,j,k) / theta00(k) * el(iprime)
endo
do iprime=G14907,G14907 + 5,1
do i=G14908,G14908 + 24,1
   ia = i + ii(iprime)
do j=G14909,G14909 + 24,1
   ja = j + jj(iprime)
   buoyancy_gen(i,j,iprime,k) = -1.0 * g * theta(ia,ja,k) / theta00(k) * el(iprime)
endo
do iprime=1,nside,1
do i=2,im2nghost-1,1
   ia = i + ii(iprime)
do j=2,jm2nghost-1,1
   ja = j + jj(iprime)
   buoyancy_gen(i,j,iprime,k) = -1.0 * g * (theta(ia,ja,k) - theta(i,j,k)) / theta00(k) * el(iprime)
endo
Auto-tuning Results

Autotuning Results for Buoyancy Loop, 16KB and 32KB Cache

Cycles (Lower is Better)

Loop Version

32K Cache
32K Cache Baseline
16K Cache
16K Cache Baseline

Shoaib Kamil UC Berkeley
Co-tuning: feedback on chip design

• We are fully profiling each loop in the code ->

• Auto-tuning can reduce the number of instructions but changes the mix of instructions.
  – Iterate this information in the chip design

• Example: the loop with the largest footprint
  • decreased the cache footprint from 160kb to 1kb
  • halved the instruction count

unique_addrs
unique_clines
footprint
footprintcache
tot_ins
Bytes/Inst
Bandwidth (MB/s)
fpload
fpstore
FP Arith
fpmov fprf
FP L/S
intload
intstore
intmov
Int Arith
Int L/S
j/call
branch
control
loop entry
Control
bitwise
shift
Logic
Hardware/Software Co-tuning

- The information from auto-tuning is relevant to the optimal chip design
- Iterate on the design process and autotuning

Marghoob Mohiyuddin, UC Berkeley
How long does it take for a full scale application to influence architectures?

Synthesize SoC (Hours)

Cycle Time
1-2 Days

Auto-Tune Software (Hours-days)

Build Application

Emulate Hardware RAMP (Hours)
A strawman design concept

• CSU icosahedral code
  – 167,772,162 vertices, ~128 vertical levels

• A strawman design concept
  – 2,621,440 horizontal subdomains (logically rectangular, 8x8 cells each)
  – 8 vertical subdomains of 16 levels each.
    • 20,971,520 processing cores.
    • 163,840 chips with 128 cores each.
    • Specific processor and network properties to be determined from the code requirement model.
Code Requirements Model

• Preliminary results for CSU code
  – 167,772,162 vertices, ~128 vertical levels

• Anelastic Dynamics only (w/o multigrid solve)
  – Sustained speed of 12 Pflops (600 Mflop per processor)
  – Total memory 560TB (27MB per processor)
  – 7623 messages per second per processor
  – Bandwidth 78MB/sec per processor

• Strong scaling w/ smaller domains
  – 10x lower latency & higher BW on chip
  – Many-core actually enables 20 million way parallelism!
Multigrid solver

- The MG solve is communication bound if the subdomains are too small.
- But multi-core chips helps this dramatically by reducing the communication costs of first few levels of the solve.
- 165K chips is better than 21M!!
We examined three different approaches (in 2009 technology)

- **AMD Opteron**: Commodity approach, lower efficiency for scientific codes offset by advantages of mass market. Constrained by legacy/binary compatibility.

- **BlueGene**: Generic embedded processor core and customize system-on-chip (SoC) to improve power efficiency for scientific applications

- **Tensilica XTensa**: Customized embedded CPU w/SoC provides further power efficiency benefits but maintains programmability. Mainstream design process, tool chain, commodity IP

<table>
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<tr>
<th>Processor</th>
<th>Clock</th>
<th>Peak/Core (Gflops)</th>
<th>Cores/Socket</th>
<th>Sockets</th>
<th>Cores</th>
<th>Power</th>
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<tr>
<td>AMD Opteron</td>
<td>2.2GHz</td>
<td>8.8</td>
<td>6</td>
<td>1.8M</td>
<td>11M</td>
<td>142MW</td>
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<tr>
<td>IBM BG/P</td>
<td>0.8GHz</td>
<td>3.4</td>
<td>4</td>
<td>7M</td>
<td>29M</td>
<td>198MW</td>
</tr>
<tr>
<td>Green Flash / Tensilica XTensa</td>
<td>1GHz</td>
<td>4</td>
<td>64</td>
<td>0.4M</td>
<td>25M</td>
<td>5 MW</td>
</tr>
</tbody>
</table>
Climate Modeling System
Strawman 100PF Design

~500 m²
~5MWatts
$100M

VLIW CPU:
- 128b load-store + 2 DP MUL/ADD + integer op/ DMA per cycle:
- Synthesizable at 1GHz Hz in commodity 45nm
- 0.5mm² core, 1.7mm² with inst cache, data cache data RAM, DMA interface, 0.15mW/MHz
- Double precision SIMD FP : 4 ops/cycle (4 GFLOPs)
- Vectorizing compiler, lightweight communications library, cycle-accurate simulator, debugger GUI
- 8 channel DMA for streaming from on/off chip DRAM
- Nearest neighbor 2D communications grid

32 boards per rack
Power + comms
32 chip + memory clusters per board (8.2 TFLOPS @ 450W)

380 racks @ ~15KW

8 DRAM per processor chip: 50 GB/s

64 processors per 45nm chip
512 GFLOPS @ 10W
Application-driven does NOT necessitate a special purpose machine (or exotic tech)

Riken MD-Grape: Full custom ASIC design
- 1 Petaflop performance for one application using 260 kW for $9M

D.E. Shaw Anton System: Full and Semi-custom design (bio-molecular)
- Simulate 100x–1000x timescales vs any existing HPC system (~200kW)

Application-Driven Architecture (Green Flash): Semicustom design
- Highly programmable core architecture using C/C++/Fortran
- Goal of 100x power efficiency improvement vs general HPC approach
We propose a new approach to high-end computing with potentially transformational impact on science

• Choose the science target first (*climate in this case*)
• Design systems for applications (*rather than the reverse*)
• Leverage power efficient embedded technology
• Design hardware, software, scientific algorithms together using auto-tuning, co-tuning, hardware emulation
• Achieve exascale computing sooner and more cost/power efficiently

Applicable to broad range of exascale-class applications
At the exascale, numerical experimentalists must take a lesson from actual experimentalists.
A concluding thought

At the exascale, numerical experimentalists must take a lesson from actual experimentalists.

Design machines to answer specific scientific questions rather than limit our questions by available machines.
Questions?


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External Collaborators: UC Berkeley, Stanford, Colorado State University, Tensilica

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Fault Tolerance/Resilience

• Our Design does not expose unique risks
  – Faults proportional to # sockets (not # cores) and silicon surface area
  – We expose less surface area and fewer sockets with our approach

• Hard Errors
  – Spare cores in design (Cisco Metro)
  – SoC design (fewer components and fewer sockets)
  – Use solder (not sockets)

• Soft Errors
  – ECC for memory and caches
  – On-board NVRAM controller for localized checkpoint
  – Checkpoint to neighbor for rollback
Green Flash: Fault Tolerance/Resilience

• Large scale applications must tolerate node failures

• Our design does not expose unique risks
  – Faults proportional to sockets (not cores) & silicon surface area
  – Low-power manycore uses less sockets

• Hard Errors
  – Spare cores in design (Cisco Metro: 188 cores + 8 spares)
  – SystemOnChip design (fewer components → fewer sockets)

• Soft Errors
  – ECC for memory and caches
  – On-board NVRAM controller for localized checkpoint

16 Clusters of 12 cores each (192 cores!)
Sustained speed

Sustained Pflops at 1000x real time

- hydrostatic
- anelastic
Total Memory requirement

![Graph showing the relationship between distance (km) and memory requirement (MB). The graph indicates a linear decrease in memory requirement as the distance increases.]