# HPC Benchmarking

**Presentations:**

- Jack Dongarra, University of Tennessee & ORNL
  - The HPL Benchmark: Past, Present & Future
- Mike Heroux, Sandia National Laboratories
  - The HPCG Benchmark: Challenges It Presents to Current & Future Systems
- Mark Adams, LBNL
  - HPGMG: A Supercomputer Benchmark & Metric
- David A. Bader, Georgia Institute of Technology
  - Graph500: A Challenging Benchmark for High Performance Data Analytics

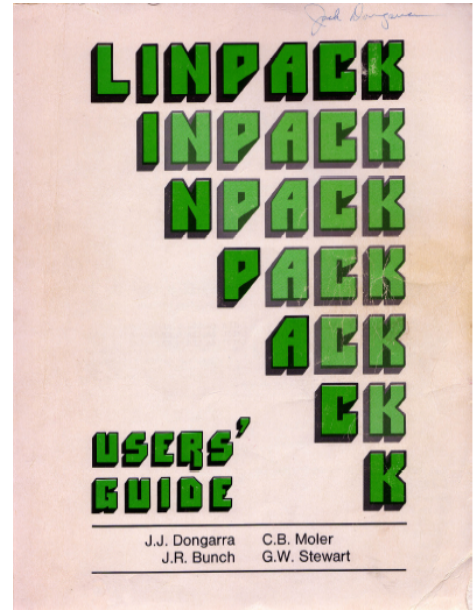
# The HPL Benchmark: Past, Present & Future

**Jack Dongarra**

University of Tennessee
Oak Ridge National Laboratory
University of Manchester

# Confessions of an Accidental Benchmarker

- Appendix B of the Linpack Users' Guide
  - Designed to help users extrapolate execution Linpack software package
- First benchmark report from 1977;
  - Cray 1 to DEC PDP-10




# Started 37 Years Ago

## Have seen a Factor of $6x10^9$ - From 14 Mflop/s to 93 Pflop/s

- In the late 70's the fastest computer ran LINPACK at 14 Mflop/s
- Today with HPL we are at 93 Pflop/s
  - Nine orders of magnitude
  - doubling every 14 months
  - About 7 orders of magnitude increase in the number of processors
  - Plus algorithmic improvements

UNIT = 10**6 TIME/( 1/3 100**3 + 100**2 )

| Facility | TIME N=100 secs. | UNIT micro-secs. | Computer | Type | Compiler |
|---|---|---|---|---|---|
| NCAR | .049 | 0.14 | CRAY-1 | S | CFT, Assembly BLAS |
| LASL | .148 | 0.43 | CDC 7600 | S | FTN, Assembly BLAS |
| NCAR | .192 | 0.56 | CRAY-1 | S | CFT |
| LASL | .210 | 0.61 | CDC 7600 | S | FTN |
| Argonne | .297 | 0.86 | IBM 370/195 | D | H |
| NCAR | .359 | 1.05 | CDC 7600 | S | Local |
| Argonne | .388 | 1.33 | IBM 3033 | D | H |
| NASA Langley | .489 | 1.42 | CDC Cyber 175 | S | FTN |
| U. Ill. Urbana | .506 | 1.47 | CDC Cyber 175 | S | Ext. 4.6 |
| LLL | .554 | 1.61 | CDC 7600 | S | CHAT, No optimize |
| SLAC | .579 | 1.69 | IBM 370/168 | D | H Ext., Fast mult. |
| Michigan | .631 | 1.84 | Amdahl 470/V6 | D | H |
| Toronto | .690 | 2.59 | IBM 370/165 | D | H Ext., Fast mult. |
| Northwestern | 1.44 | 4.20 | CDC 6600 | S | FTN |
| Texas | 1.93* | 5.63 | CDC 6600 | S | RUN |
| China Lake | 1.95* | 5.69 | Univac 1110 | S | V |
| Yale | 2.59 | 7.53 | DEC KL-20 | S | F20 |
| Bell Labs | 3.46 | 10.1 | Honeywell 6080 | S | Y |
| Wisconsin | 3.49 | 10.1 | Univac 1110 | S | V |
| Iowa State | 3.54 | 10.2 | Itel AS/5 mod3 | D | H |
| U. Ill. Chicago | 4.10 | 11.9 | IBM 370/158 | D | G1 |
| Purdue | 5.69 | 16.6 | CDC 6500 | S | FUN |
| U. C. San Diego | 13.1 | 38.2 | Burroughs 6700 | S | H |
| Yale | 17.1* | 49.9 | DEC KA-10 | S | F40 |

* TIME(100) = (100/75)**3 SGEFA(75) + (100/75)**2 SGESL(75)

Began in late 70's

time when floating point operations were expensive compared to other operations and data movement

LA-7389-MS
Informal Report
UC-32
Issued: August 1978

LINPACK

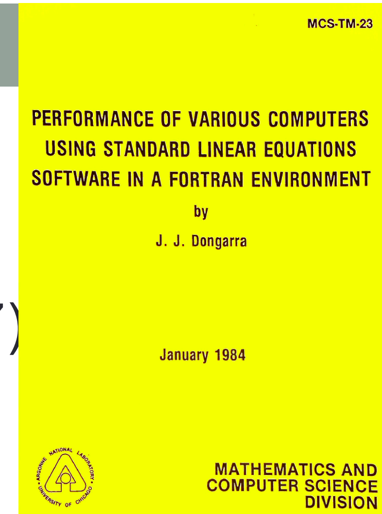
Some LINPACK

*Argonne Nation

LINPACK ANECDOTE #1

One of the interesting things uncovered by the timing was a hardware problem in the LASL CRAY-1. During the timing runs, a check was made of the answers produced by the various routines. It was discovered that codes run in two different implementations produced the wrong answers. After some investigation by T. Jordan, the CRAY-1 engineers, and me, the problem was traced to a hardware board in the arithmetic unit that adjusts the exponents of operands before vector addition. The exponent adjustment was not being performed correctly in certain instances when operating in vector mode. Incorrect results were produced when the exponent to be adjusted had a certain bit pattern, making the errors in the answers appear somewhat mysterious. When it was finally tracked down and the defective board replaced, the correct results were obtained. The interesting thing is that the CRAY-1 had been in operation at LASL for a little over two months and no one seemed to notice any problems. The machine passed its diagnostic tests every morning and many hours of production work had been completed before the problem was uncovered.

# Linpack Benchmark Over Time


MCS-TM-23

PERFORMANCE OF VARIOUS COMPUTERS
USING STANDARD LINEAR EQUATIONS
SOFTWARE IN A FORTRAN ENVIRONMENT

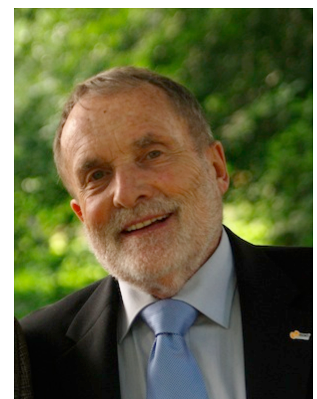
by

J. J. Dongarra

January 1984

MATHEMATICS AND
COMPUTER SCIENCE
DIVISION

- In the beginning there was the Linpack 100 Benchmark (1977)
  - n=100 (80KB); size that would fit in all the machines
  - Fortran; 64 bit floating point arithmetic
  - No hand optimization (only compiler options)
- Linpack 1000 (1986)
  - n=1000 (8MB); wanted to see higher performance levels
  - Any language; 64 bit floating point arithmetic
  - Hand optimization OK
- Linpack TPP (1991) (Top500; 1993)
  - Any size (n as large as you can; n = $12 \times 10^6$; 1.2 PB);
  - Any language; 64 bit floating point arithmetic
  - Hand optimization OK
    - Strassen's method not allowed (confuses the op count and rate)
  - Reference implementation available
- In all cases results are verified by looking at: $\frac{\| Ax - b \|}{\| A \| \| x \| \, n \, \varepsilon} = O(1)$
- Operations count for factorization $\frac{2}{3}n^3 - \frac{1}{2}n^2$; solve $2n^2$



# Rules For HPL and TOP500

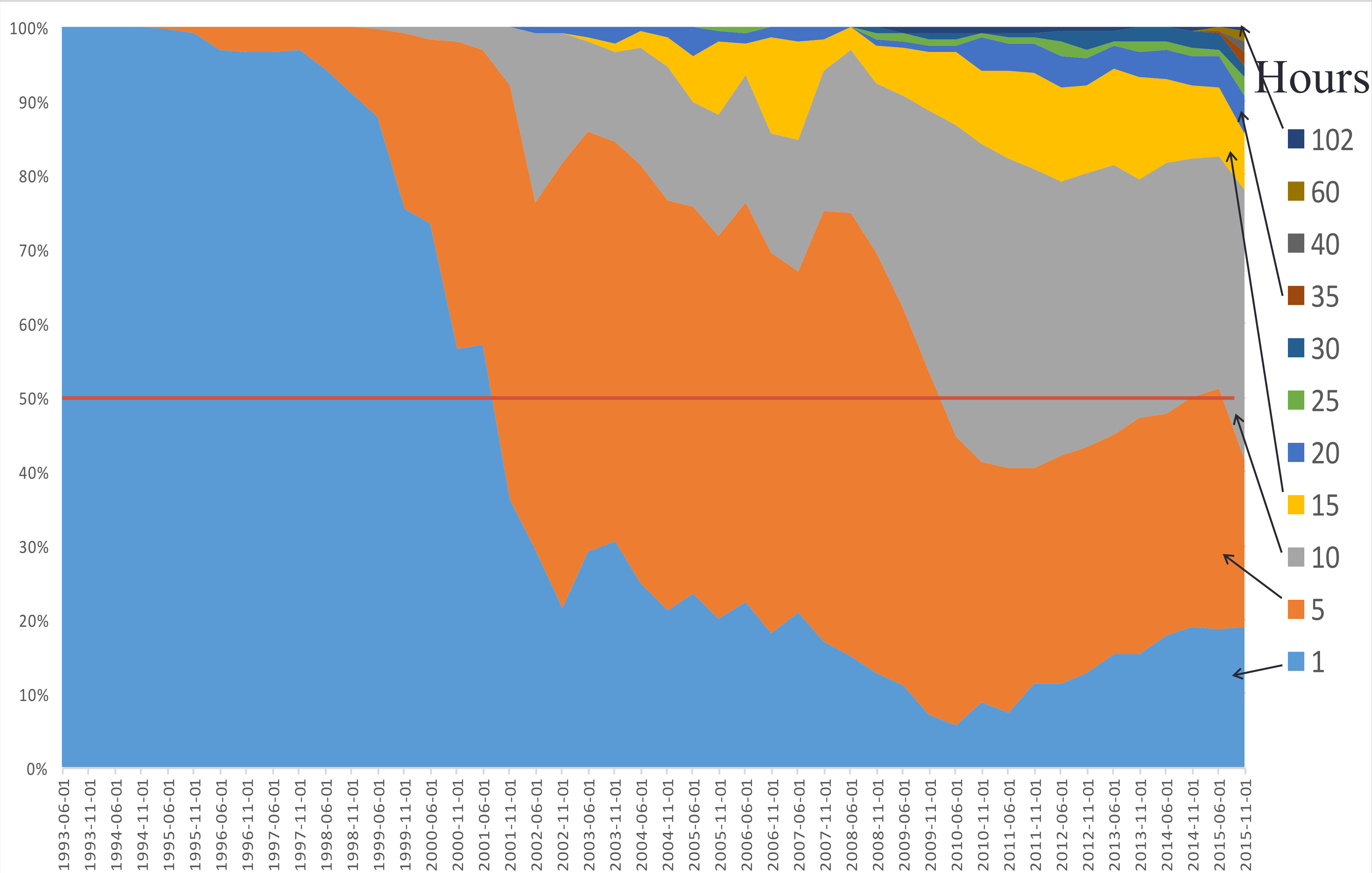
- Algorithm is Gaussian Elimination with partial pivoting.
  - Excludes the use of a fast matrix multiply algorithm like "Strassen's Method”
  - Excludes algorithms which compute a solution in a precision lower than full precision (64 bit floating point arithmetic) and refine the solution using an iterative approach.
- The authors of the TOP500 reserve the right to independently verify submitted LINPACK results, and exclude computer from the list which are not valid or not general purpose in nature.
  - Any computer designed specifically to solve the LINPACK benchmark problem or have as its major purpose the goal of a high TOP500 ranking will be disqualified.

# #1 System on the Top500 Over the Past 24 Years (18 machines in that club)

9 6 3

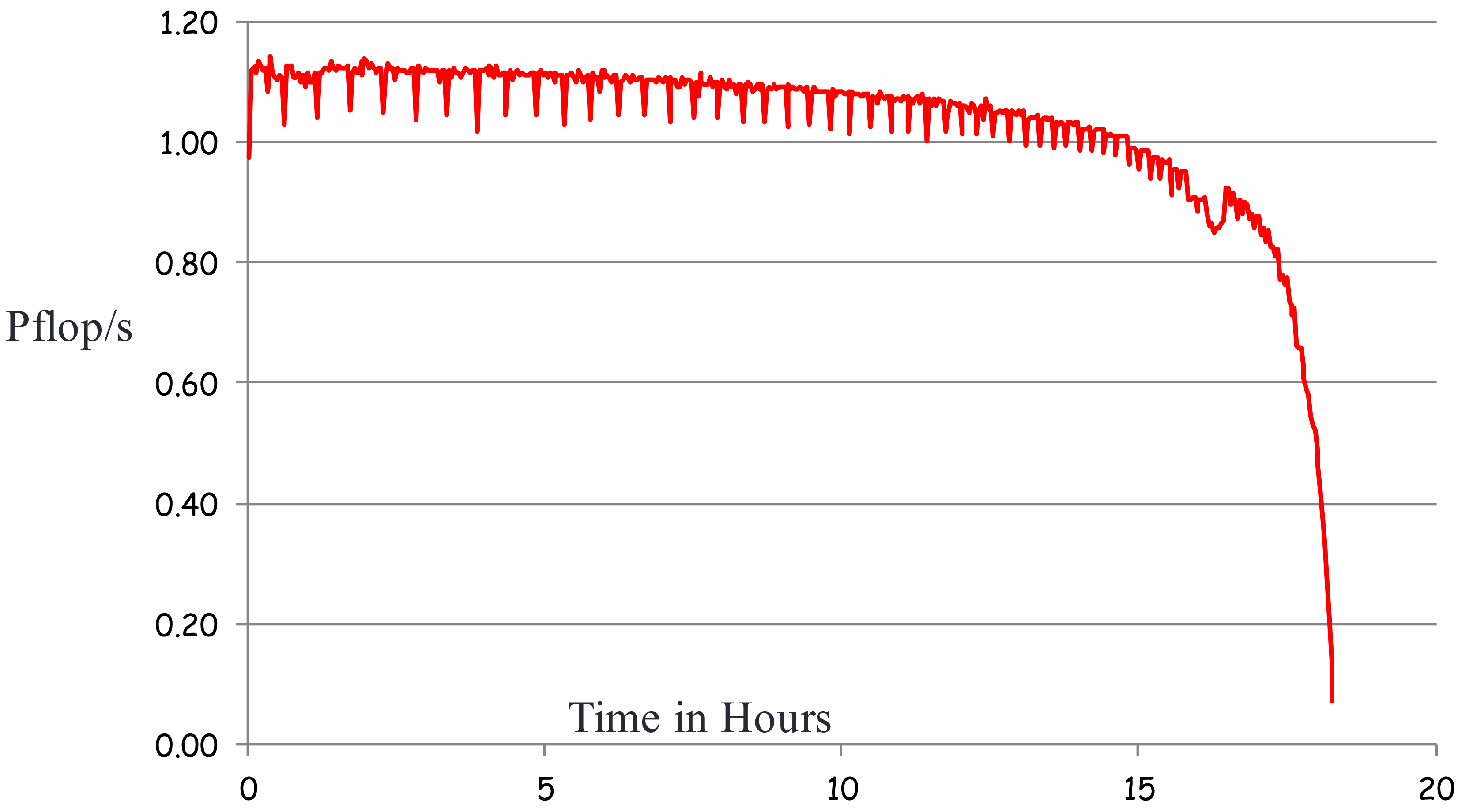
| Top500 List | Computer | r_max (Tflop/s) | n_max | Hours | MW |
|---|---|---|---|---|---|
| 6/93 (1) | TMC CM-5/1024 | .060 | 52224 | 0.4 | |
| 11/93 (1) | Fujitsu Numerical Wind Tunnel | .124 | 31920 | 0.1 | 1. |
| 6/94 (1) | Intel XP/S140 | .143 | 55700 | 0.2 | |
| 11/94 - 11/95 (3) | Fujitsu Numerical Wind Tunnel | .170 | 42000 | 0.1 | 1. |
| 6/96 (1) | Hitachi SR2201/1024 | .220 | 138,240 | 2.2 | |
| 11/96 (1) | Hitachi CP-PACS/2048 | .368 | 103,680 | 0.6 | |
| 6/97 - 6/00 (7) | Intel ASCI Red | 2.38 | 362,880 | 3.7 | .85 |
| 11/00 - 11/01 (3) | IBM ASCI White, SP Power3 375 MHz | 7.23 | 518,096 | 3.6 | |
| 6/02 - 6/04 (5) | NEC Earth-Simulator | 35.9 | 1,000,000 | 5.2 | 6.4 |
| 11/04 - 11/07 (7) | IBM BlueGene/L | 478. | 1,000,000 | 0.4 | 1.4 |
| 6/08 - 6/09 (3) | IBM Roadrunner –PowerXCell 8i 3.2 Ghz | 1,105. | 2,329,599 | 2.1 | 2.3 |
| 11/09 - 6/10 (2) | Cray Jaguar - XT5-HE 2.6 GHz | 1,759. | 5,474,272 | 17.3 | 6.9 |
| 11/10 (1) | NUDT Tianhe-1A, X5670 2.93Ghz NVIDIA | 2,566. | 3,600,000 | 3.4 | 4.0 |
| 6/11 - 11/11 (2) | Fujitsu K computer, SPARC64 VIIIfx | 10,510. | 11,870,208 | 29.5 | 9.9 |
| 6/12 (1) | IBM Sequoia BlueGene/Q | 16,324. | 12,681,215 | 23.1 | 7.9 |
| 11/12 (1) | Cray XK7 Titan AMD + NVIDIA Kepler | 17,590. | 4,423,680 | 0.9 | 8.2 |
| 6/13 - 11/15(6) | NUDT Tianhe-2 Intel IvyBridge & Xeon Phi | 33,862. | 9,960,000 | 5.4 | 17.8 |
| 6/16 - | Sunway TaihuLight System | 93,014. | 12,288,000 | 3.7 | 15.4 |

# Run Times for HPL on Top500 Systems



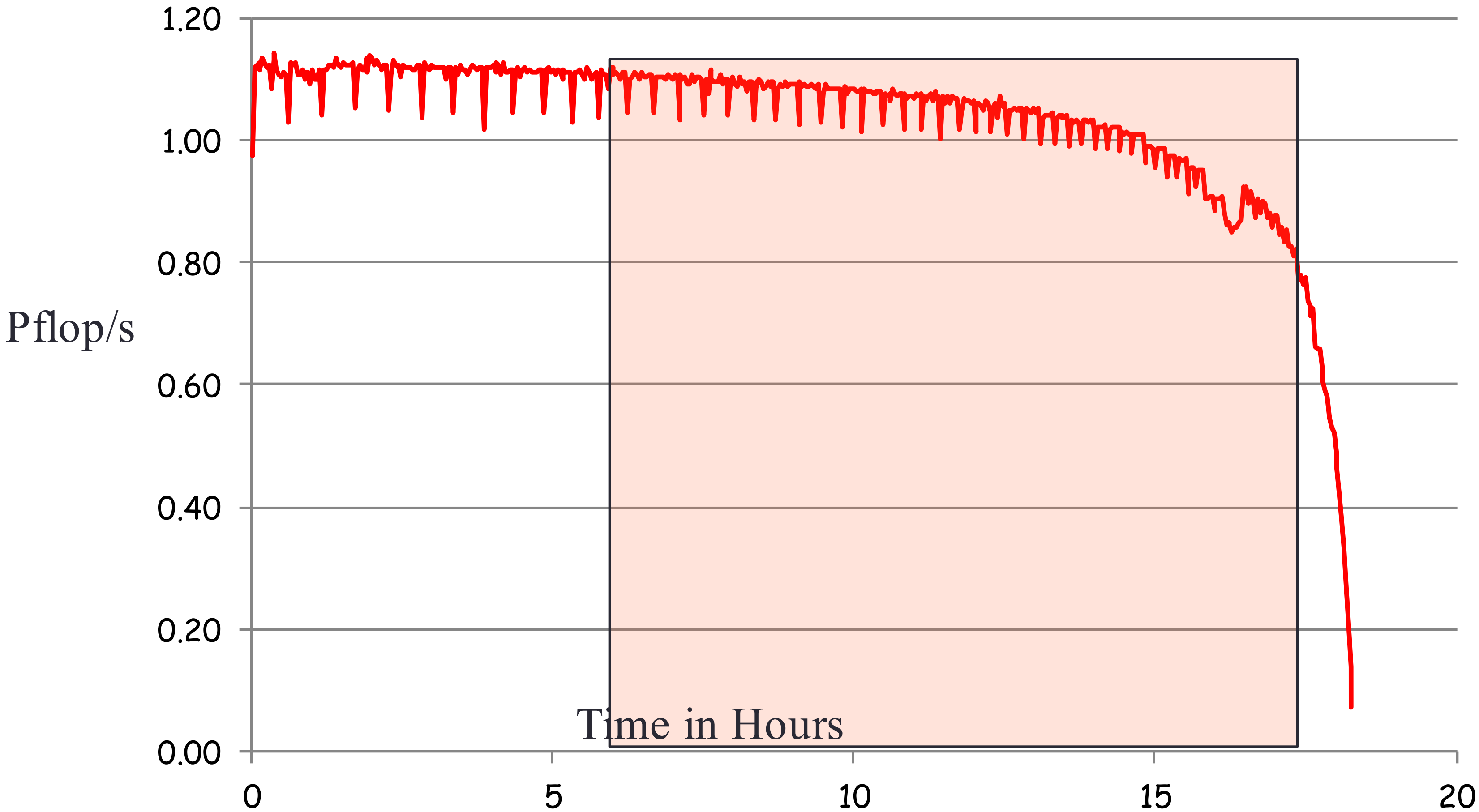
# Over the Course of the Run

- Can’t just start the run and stop it.
- The performance will vary over the course of the run.



# How to Capture Performance?

- Determine the section where the computation and communications for the execution reflect a completed run.

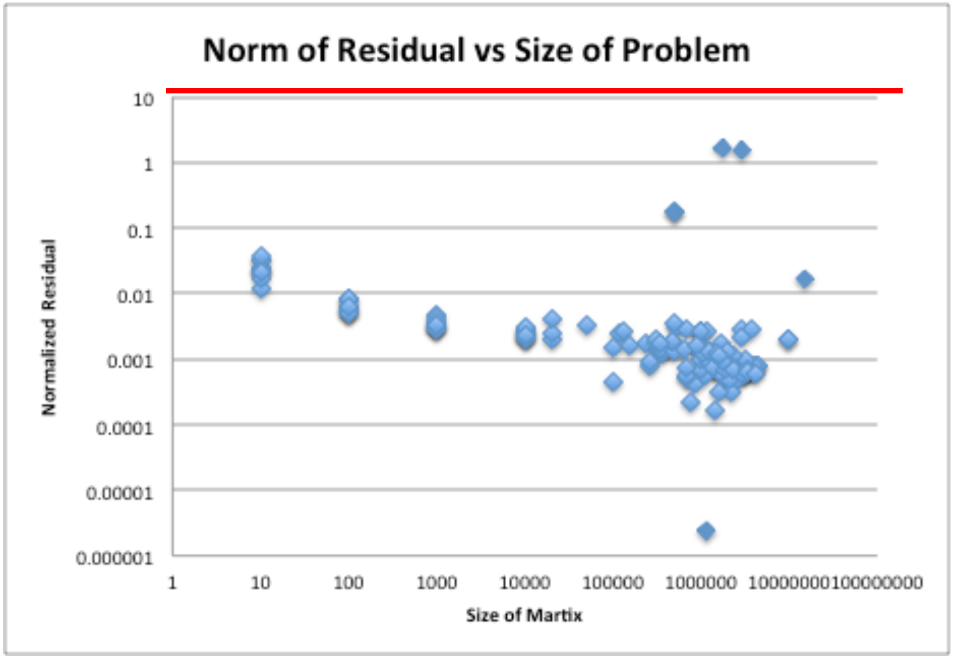


# LINPACK Benchmark – Still Learning Things

- We use a backwards error residual to check the "correctness" of the solution.

$$\frac{\|b - Ax\|_\infty}{\varepsilon N \left(\|b\|_\infty + \|A\|_\infty \|x\|_\infty\right)}$$

- This is the classical Wilkinson error bound.
  - If the residual is small O(1) then the software is doing the best it can independent of the conditioning of the matrix.
- We say O(1) is OK, the code allows the residual to be less than O(10).
- For large problems we noticed the residual was getting smaller.



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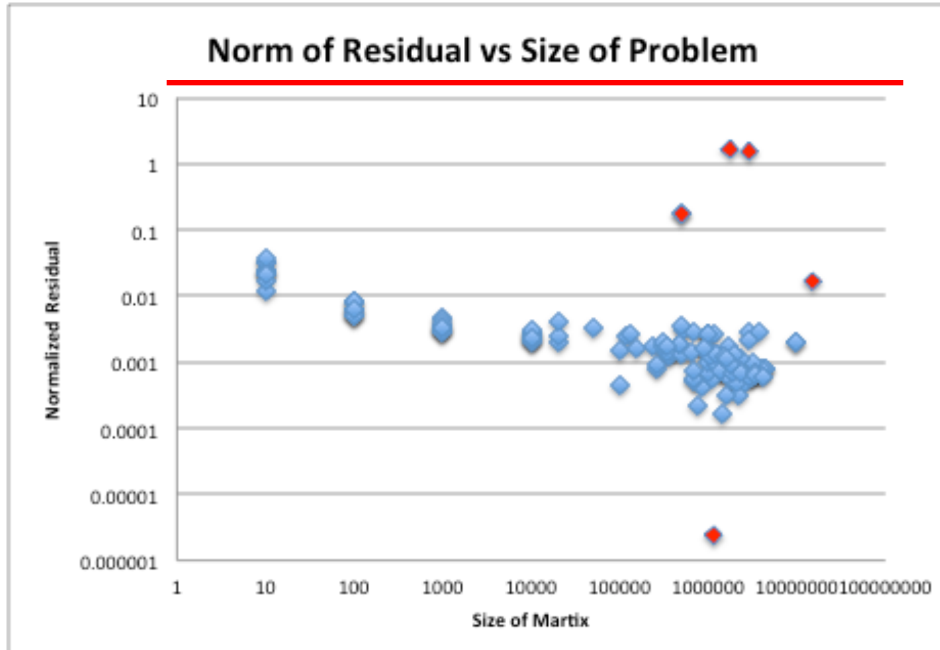


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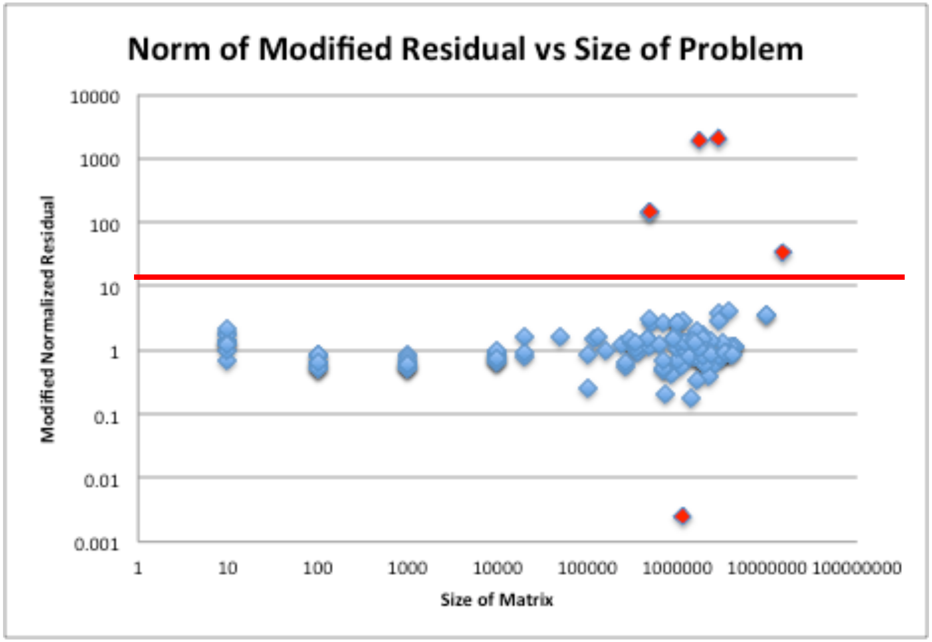
# LINPACK Benchmark – Still Learning Things

- The current criteria might be about $O(10^3)$ too lax which allows error for the last 10-12 bits of the mantissa to go undetected.
- We believe this has to do with the rounding errors for collective ops when done in parallel, i.e. MatVec and norms
- A better formulation of the residual might be:




$$\frac{32\|b - Ax\|_\infty}{\varepsilon N^{\frac{3}{4}} \left(\|b\|_\infty + \|A\|_\infty \|x\|_\infty\right)}$$

# HPL - Bad Things

- LINPACK Benchmark is 37 years old
  - TOP500 (HPL) is 23 years old
- Floating point-intensive performs $O(n^3)$ floating point operations and moves $O(n^2)$ data.
- No longer so strongly correlated to real apps.
- Reports Peak Flops (although hybrid systems see only 1/2 to 2/3 of Peak)
- Encourages poor choices in architectural features
- Overall usability of a system is not measured
- Used as a marketing tool
- Decisions on acquisition made on one number
- Benchmarking for days wastes a valuable resource

hpcg-benchmark.org

# HPCG UPDATE: ISC'16

Jack Dongarra
Michael Heroux
Piotr Luszczek

hpcg-benchmark.org

# HPCG Snapshot

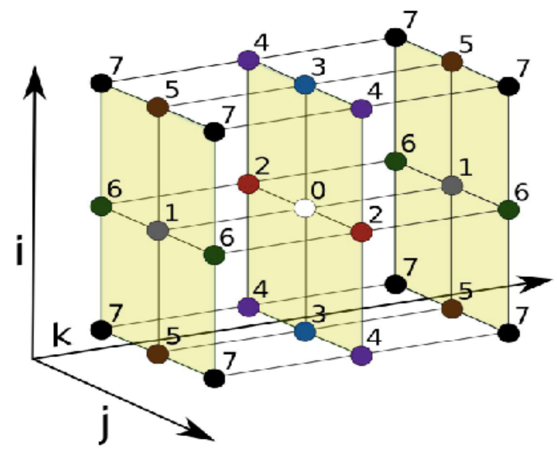
- High Performance Conjugate Gradients (HPCG).
- Solves $Ax=b$, $A$ large, sparse, $b$ known, $x$ computed.
- An optimized implementation of PCG contains essential computational and communication patterns that are prevalent in a variety of methods for discretization and numerical solution of PDEs

- Patterns:
  - Dense and sparse computations.
  - Dense and sparse collectives.
  - Multi-scale execution of kernels via MG (truncated) V cycle.
  - Data-driven parallelism (unstructured sparse triangular solves).
- Strong verification (via spectral properties of PCG).

hpcg-benchmark.org

# Model Problem Description

- Synthetic discretized 3D PDE (FEM, FVM, FDM).
- Zero Dirichlet BCs, Synthetic RHS s.t. solution = 1.
- Local domain: $(n_x \times n_y \times n_z)$
- Process layout: $(np_x \times np_y \times np_z)$
- Global domain: $(n_x * np_x) \times (n_y * np_y) \times (n_z * np_z)$
- Sparse matrix:
  - 27 nonzeros/row interior.
  - 8 – 18 on boundary.
  - Symmetric positive definite.




27-point stencil operator

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# Merits of HPCG

- Includes major communication/computational patterns.
  - Represents a minimal collection of the major patterns.
- Rewards investment in:
  - High-performance collective ops.
  - Local memory system performance.
  - Low latency cooperative threading.
- Detects/measures variances from bitwise reproducibility.
- Executes kernels at several (tunable) granularities:
  - nx = ny = nz = 104 gives
  - nlocal = 1,124,864; 140,608; 17,576; 2,197
  - ComputeSymGS with multicoloring adds one more level:
    - 8 colors.
    - Average size of color = 275.
    - Size ratio (largest:smallest): 4096
  - Provide a “natural” incentive to run a big problem.

# HPL vs. HPCG: Bookends

- Some see HPL and HPCG as “bookends” of a spectrum.
  - Applications teams know where their codes lie on the spectrum.
  - Can gauge performance on a system using both HPL and HPCG numbers.

# *HPCG Status*

# HPCG 3.0 Release, Nov 11, 2015

- Available on GitHub.com
  - Using GitHub issues, pull requests, Wiki.
- Optimized 3.0 version:
  - Vendor or site developed.
  - Used for all results (AFAWK).
  - Intel, Nvidia, IBM: Available to their customers.
- All future results require HPCG 3.0 use.
- Quick Path option makes this easier.

# Main HPCG 3.0 Features



See http://www.hpcg-benchmark.org/software/index.html for full discussion

- Problem generation is timed.
- Memory usage counting and reporting.
- Memory bandwidth measurement and reporting
- "Quick Path" option to make obtaining results on production systems easier.
- Provides 2.4 rating and 3.0 rating in output.
- Command line option (--rt=) to specify the run time.

# Other Items

- Reference version on GitHub:
  - https://github.com/hpcg-benchmark/hpcg
  - Website: hpcg-benchark.org.
  - Mail list hpcg.benchmark@gmail.com
- HPCG & Student Cluster Competitions.
  - Used in SC15/16, ASC
  - SC15: HPCG replaced HPL, ranking matched overall cluster ranking.
- HPCG-optimized kernels going into vendor libraries.
- Next event: SC'16:
  - 80 entries ISC16
  - 61 – SC15, 42 – ISC15, 25 – SC14, 15 – ISC14

# Summary

- HPCG is
  - Addressing original goals.
  - Rewarding vendor investment in features we care about.
- HPCG has traction.
  - Original goal of top 50 systems is reachable, and more.
- Version 3.X is the final planned major version.
- HPL and HPCG make a nice set of bookends.
  - Anyone got a (wood) router?

hpcg-benchmark.org

# HPCG RANKINGS JUNE 2016

hpcg-benchmark.org

# And The Winners Are…


HPCG
PRESENTED AT
ISC High Performance
JUNE 21, 2016
NUMBER 3
SYSTEM Sunway TaihuLight
National Supercomputing Center in Wuxi
CHINA
ACHIEVED 0.371 Pflop/s
JACK DONGARRA
MICHAEL HEROUX
PIOTR LUSZCZEK
IN COLLABORATION WITH
ICL UT INNOVATIVE COMPUTING LABORATORY
Sandia National Laboratories
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HPCG
PRESENTED AT
ISC High Performance
JUNE 21, 2016
NUMBER 2
SYSTEM K computer
RIKEN Advanced Institute for Computational Science
JAPAN
ACHIEVED 0.554 Pflop/s
JACK DONGARRA
MICHAEL HEROUX
PIOTR LUSZCZEK
IN COLLABORATION WITH
ICL UT INNOVATIVE COMPUTING LABORATORY THE UNIVERSITY of TENNESSEE
Sandia National Laboratories
SPONSORED BY


HPCG
PRESENTED AT
ISC High Performance
JUNE 21, 2016
NUMBER 1
SYSTEM Tianhe-2
National Super Computer Center in Guangzhou
CHINA
ACHIEVED 0.580 Pflop/s
JACK DONGARRA
MICHAEL HEROUX
PIOTR LUSZCZEK
IN COLLABORATION WITH
ICL UT INNOVATIVE COMPUTING LABORATORY
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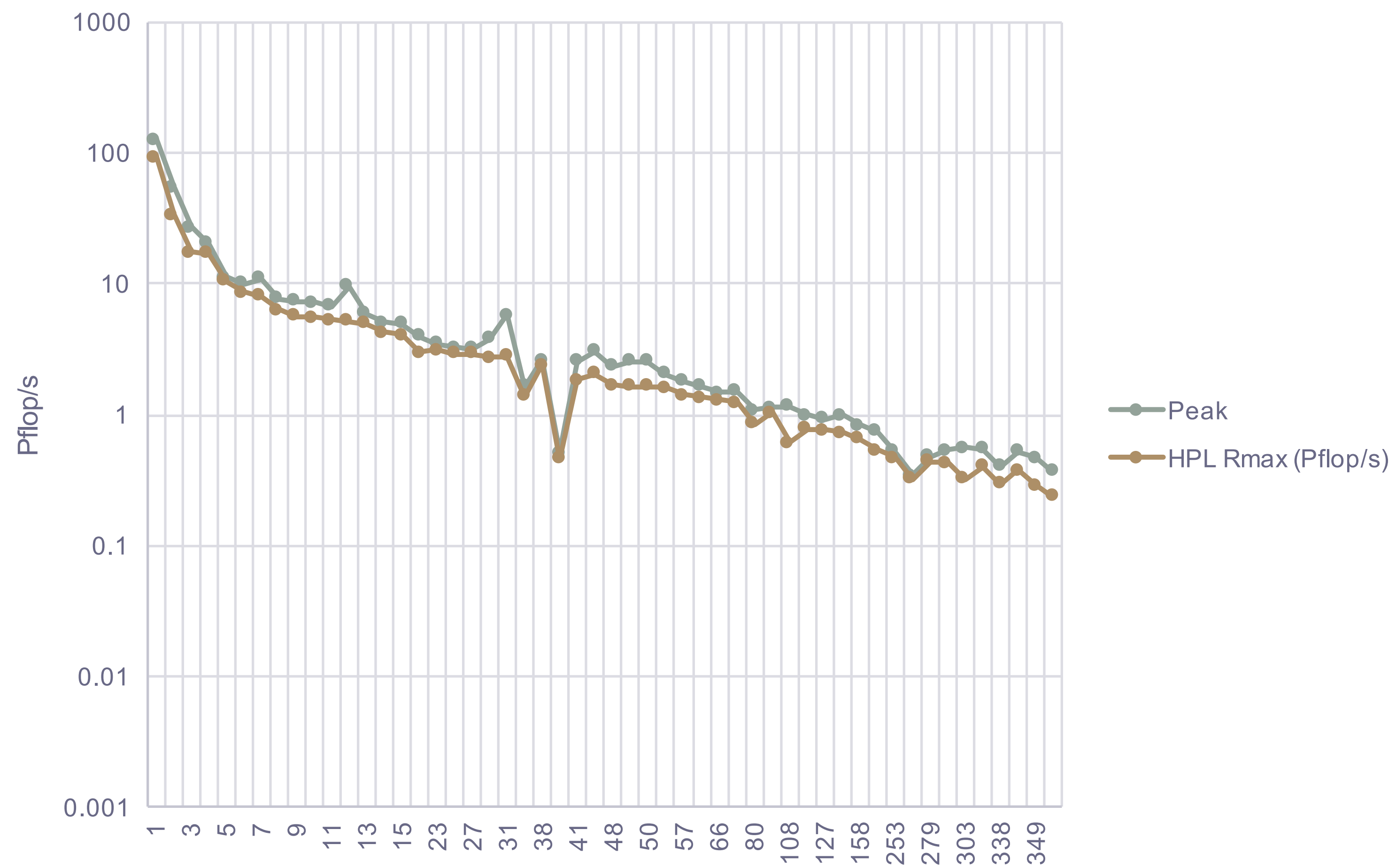
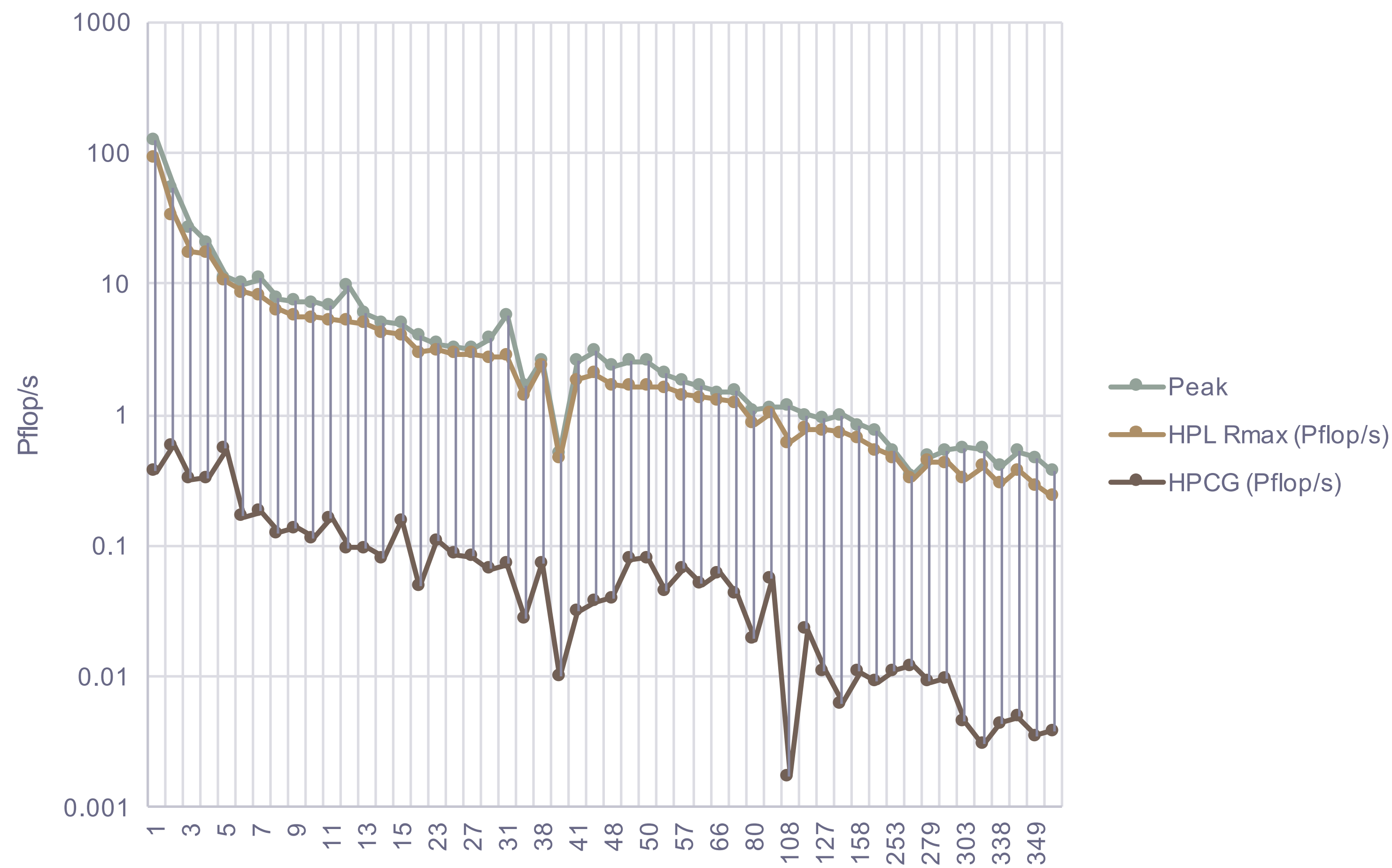
# 1-10

| Rank (HPL) | Site | Computer | Cores | Rmax | HPCG | HPCG/HPL | % of Peak |
|---|---|---|---|---|---|---|---|
| 1 (2) | NSCC / Guangzhou | Tianhe-2 NUDT, Xeon 12C 2.2GHz + Intel Xeon Phi 57C + Custom | 3,120,000 | 33.863 | 0.5800 | 1.7% | 1.1% |
| 2 (5) | RIKEN Advanced Institute for Computational Science | K computer, SPARC64 VIIIfx 2.0GHz, Tofu interconnect | 705,024 | 10.510 | 0.5544 | 5.3% | 4.9% |
| 3 (1) | National Supercomputing Center in Wuxi | Sunway TaihuLight -- SW26010, Sunway | 10,649,600 | 93.015 | 0.3712 | 0.4% | 0.3% |
| 4 (4) | DOE/NNSA/LLNL | Sequoia - IBM BlueGene/Q | 1,572,864 | 17.173 | 0.3304 | 1.9% | 1.6% |
| 5 (3) | DOE/SC/Oak Ridge Nat Lab | Titan - Cray XK7 , Opteron 6274 16C 2.200GHz, Cray Gemini interconnect, NVIDIA K20x | 560,640 | 17.590 | 0.3223 | 1.8% | 1.2% |
| 6 (7) | DOE/NNSA/LANL/SNL | Trinity - Cray XC40, Intel E5-2698v3, Aries custom | 301,056 | 8.101 | 0.1826 | 2.3% | 1.6% |
| 7 (6) | DOE/SC/Argonne National Laboratory | Mira - BlueGene/Q, Power BQC 16C 1.60GHz, Custom | 786,432 | 8.587 | 0.1670 | 1.9% | 1.7% |
| 8 (11) | TOTAL | Pangea -- Intel Xeon E5-2670, Infiniband FDR | 218592 | 5.283 | 0.1627 | 3.1% | 2.4% |
| 9 (15) | NASA / Mountain View | Pleiades - SGI ICE X, Intel E5-2680, E5-2680V2, E5-2680V3, Infiniband FDR | 185,344 | 4.089 | 0.1555 | 3.8% | 3.1% |
| 10 (9) | HLRS/University of Stuttgart | Hazel Hen - Cray XC40, Intel E5-2680v3, Cray Aries | 185,088 | 5.640 | 0.1380 | 2.4% | 1.9% |

# Bookends: Peak, HPL, and HPCG



# Bookends: Peak, HPL, and HPCG



hpcg-benchmark.org

# HPCG Highlights

- 80 Systems:
  - Up from 61 at SC’15, 42 at ISC’15, 25 at SC’14 and 15 at ISC’14.
  - All of the top 10, most of the top 20.
- Notable new entries are:
  - New #3: Sunway TaihuLight, HPL #1
  - New #4: Sequoia, HPL #4.
- Expect upgraded Trinity result (with KNL) for SC’16.
- HPCG has diverse adoption:
  - Vendor/site versions complete.
  - Cluster competitions.
  - Industry analysis.

# 11-20

| Rank | Site | Computer | Cores | Rmax | HPCG | HPCG/HPL | % of Peak |
|---|---|---|---|---|---|---|---|
| 11 | Swiss National Supercomputing Centre (CSCS) | Piz Daint - Cray XC30, Xeon E5-2670 8C 2.600GHz, Aries interconnect , NVIDIA K20x | 115,984 | 6.271 | 0.1246 | 2.0% | 1.6% |
| 12 | KAUST / Jeddah | Shaheen II - Cray XC40, Intel Haswell 2.3 GHz 16C, Cray Aries | 196,608 | 5.537 | 0.1139 | 2.1% | 1.6% |
| 13 | Japan Aerospace eXploration Agency | SORA-MA -- SPARC64 XIfx | 103,680 | 3.157 | 0.1102 | 3.5% | 3.2% |
| 14 | Texas Advanced Computing Center/Univ. of Texas | Stampede - PowerEdge C8220, Xeon E5-2680 8C 2.700GHz, Infiniband FDR, Intel Xeon Phi SE10P | 522,080 | 5.168 | 0.0968 | 1.9% | 1.0% |
| 15 | Forschungszentrum Jülich | JUQUEEN - BlueGene/Q | 458,752 | 5.009 | 0.0955 | 1.9% | 1.6% |
| 16 | Information Technology Center, Nagoya University | ITC, Nagoya - Fujitsu PRIMEHPC FX100, SPARC64 Xifx, Tofu interconnect 2 | 92,160 | 2.910 | 0.0865 | 3.0% | 2.7% |
| 17 | Leibniz Rechenzentrum | SuperMUC - iDataPlex DX360M4, Xeon E5-2680 8C 2.70GHz, Infiniband FDR | 147,456 | 2.897 | 0.0833 | 2.9% | 2.6% |
| 18 | DOE/NNSA/LLNL | Vulcan - IBM BlueGene/Q | 393,216 | 4.293 | 0.0809 | 1.9% | 1.6% |
| 19 | EPSRC/University of Edinburgh | ARCHER - Cray XC30, Intel Xeon E5 v2 12C 2.700GHz, Aries interconnect | 118,080 | 1.643 | 0.0808 | 4.9% | 3.2% |
| 20 | DOE/SC/LBNL/NERSC | Edison - Cray XC30, Intel Xeon E5-2695v2 12C 2.4GHz, Aries interconnect | 133,824 | 1.655 | 0.0786 | 4.8% | 3.1% |

# 21-30

| Rank | Site | Computer | Cores | Rmax | HPCG | HPCG/HPL | % of Peak |
|---|---|---|---|---|---|---|---|
| 21 | National Institute for Fusion Science | Plasma Simulator - Fujitsu PRIMEHPC FX100, SPARC64 Xifx, Tofu Interconnect 2 | 82,944 | 2.376 | 0.0732 | 3.1% | 2.8% |
| 22 | GSIC Center, Tokyo Institute of Technology | TSUBAME 2.5 - Cluster Platform SL390s G7, Xeon X5670 6C 2.93GHz, Infiniband QDR, NVIDIA K20x | 76,032 | 2.785 | 0.0725 | 2.6% | 1.3% |
| 23 | Forschungszentrum Jülich | JURECA - T-Platform V-Class Cluster, Xeon E5-2680v3 12C 2.5GHz, Infiniband EDR, NVIDIA Tesla K80/K40 | 49,476 | 1.425 | 0.0683 | 4.8% | 3.8% |
| 24 | HLRS/Universitaet Stuttgart | Hornet - Cray XC40, Xeon E5-2680 v3 2.5 GHz, Cray Aries | 94,656 | 2.763 | 0.0661 | 2.4% | 1.7% |
| 25 | Max-Planck-Gesellschaft MPI/IPP | iDataPlex DX360M4, Intel Xeon E5-2680v2 10C 2.800GHz, Infiniband FDR | 65,320 | 1.283 | 0.0615 | 4.8% | 4.2% |
| 26 | CEIST / JAMSTEC | Earth Simulator - NEC SX-ACE | 8,192 | 0.487 | 0.0578 | 11.9% | 11.0% |
| 27 | Information Technology Center, The University of Tokyo | Oakleaf-FX -- SPARC64 Ixfx | 76,800 | 1.043 | 0.0565 | 5.4% | 5.0% |
| 28 | CEIST / JAMSTEC | Earth Simulator -- NEC SX-ACE | 8,192 | 0.487 | 0.0547 | 11.2% | 10.4% |
| 29 | CEA/TGCC-GENCI | Curie thin nodes - Bullx B510, Xeon E5-2680 8C 2.700GHz, Infiniband QDR | 77,184 | 1.359 | 0.0510 | 3.8% | 3.1% |
| 30 | Exploration & Production - Eni S.p.A. | HPC2 - iDataPlex DX360M4, Intel Xeon E5-2680v2 10C 2.8GHz, Infiniband FDR, NVIDIA K20x | 62,640 | 3.003 | 0.0489 | 1.6% | 1.2% |

# 31-40

| Rank | Site | Computer | Cores | Rmax | HPCG | HPCG/HPL | % of Peak |
|---|---|---|---|---|---|---|---|
| 31 | Grand Equipement National de Calcul Intensif - Centre Informatique National de l'Enseignement Superieur (GENCI-CINES) | Occigen Bullx B720, Xeon E5-2690v3 12C 2.600GHz, InfiniBand FDR | 50,544 | 1.629 | 0.0455 | 2.8% | 2.2% |
| 32 | International Fusion Energy Research Centre (IFERC), EU(F4E) - Japan Broader Approach collaboration | Helios Bullx B510, Xeon E5-2680 8C 2.700GHz, Infiniband QDR | 70,560 | 1.237 | 0.0426 | 3.4% | 2.8% |
| 33 | Cyfronet | Prometheus - HP ProLiant Intel E5-2680v3, Infiniband FDR | 55,728 | 1.670 | 0.0399 | 2.4% | 1.7% |
| 34 | Lvliang/National University of Defense Technology | Tianhe-2 Lvliang - Intel Xeon E5-2692v2 12C, TH Express-2, Intel Xeon Phi 31S1P | 174,720 | 2.071 | 0.0376 | 1.8% | 1.2% |
| 35 | Moscow State University / Research Computing Center | Lomonosov 2 - Intel Xeon E5-2680V2, Infiniband FDR, NVIDIA K40 | 37,120 | 1.849 | 0.0315 | 1.7% | 1.2% |
| 36 | DKRZ - Deutsches Klimarechenzentrum | Mistral -- Intel Xeon E5-2695v4, Infiniband FDR | 19,200 | 1.371 | 0.0283 | 2.1% | 1.7% |
| 37 | Cyberscience Center, Tohoku University | Cyberscience Center, Tohoku University -- NEC SX-ACE | 4,096 | 0.246 | 0.0279 | 11.3% | 10.7% |
| 38 | Stanford University / Palo Alto | Xstream - Dual Intel E5-2680V2, 8-way NVIDIA K80, Infiniband FDR | 237,120 | 0.781 | 0.0230 | 2.9% | 2.3% |
| 39 | CINECA | Fermi - IBM BlueGene/Q | 163,840 | 1.789 | 0.0216 | 1.2% | 1.0% |
| 40 | SURFsara, Amsterdam | Cartesius2 bullx B720, dual socket Intel Xeon E5-2690 v3, Infiniband FDR | 25,920 | 0.848 | 0.0195 | 2.3% | 1.8% |

# 41-50

| Rank | Site | Computer | Cores | Rmax | HPCG | HPCG/HPL | % of Peak |
|---|---|---|---|---|---|---|---|
| 41 | Cyberscience Center / Tohoku University | NEC SX-ACE 4C+IXS | 2,048 | 0.123 | 0.0150 | 12.2% | 11.4% |
| 42 | Cybermedia Center, Osaka University | Osaka U ACE -- NEC SX-ACE | 2,048 | 0.123 | 0.0142 | 11.5% | 10.8% |
| 43 | SGI | SGI ICE X -- Intel Xeon E5-2690v4, Infiniband EDR | 16,128 | 0.602 | 0.0122 | 2.0% | 1.8% |
| 44 | LNCC | Santos Dumont, Bullx Intel E5-2695v2, Infiniband FDR | 17,616 | 0.321 | 0.0121 | 3.8% | 3.5% |
| 45 | Intel | Endeavor - Intel Cluster, Dual Intel Xeon E5-2697v3 14C 2.700GHz, Infiniband FDR, Intel Xeon Phi 7120P | 51,392 | 0.759 | 0.0112 | 1.5% | 1.2% |
| 46 | Meteo France | Beaufix - Bullx DLC B710 Blades, Intel Xeon E5-2697v2 12C 2.7GHz, Infiniband FDR | 24,192 | 0.469 | 0.0110 | 2.3% | 2.1% |
| 47 | Saint Petersburg Polytechnic University | Polytechnic - RSC Tornado Intel E52697v3, Infiniband FDR | 17,444 | 0.658 | 0.0108 | 1.6% | 1.3% |
| 48 | Meteo France | Prolix - Bullx DLC B710 Blades, Intel Xeon E5-2697v2 12C 2.7GHz, Infiniband FDR | 23,760 | 0.465 | 0.0100 | 2.1% | 1.9% |
| 49 | Bull Angers | Manny Bullx B720, Xeon E5-2690v3 12C 2.600GHz, InfiniBand FDR | 12,960 | 0.430 | 0.0097 | 2.3% | 1.8% |
| 50 | University Heidelberg and University Mannheim | bwForCluster - Intel E5-2630v3, Infiniband QDR | 7,552 | 0.241 | 0.0093 | 3.9% | 3.2% |

# 51-60

| Rank | Site | Computer | Cores | Rmax | HPCG | HPCG/HPL | % of Peak |
|---|---|---|---|---|---|---|---|
| 51 | Michigan State University | Laconia -- Intel Xeon E5-2680v4, Infiniband EDR FDR | 1,008,760 | 0.536 | 0.0091 | 1.7% | 1.2% |
| 52 | University of Duisburg-Essen | magnitUDE -- Intel Xeon E5-2650v4, Intel OmniPath | 12 | 0.437 | 0.0090 | 2.1% | 1.9% |
| 53 | CALMIP / University of Toulouse | EOS - Bullx DLC B710 Blades, Intel Xeon E5-2680v2 10C 2.8GHz, Infiniband FDR | 12,240 | 0.255 | 0.0073 | 2.8% | 2.6% |
| 54 | Christian-Albrechts-Universitaet zu Kiel | NEC SX-ACE -- NEC SX-ACE | 1,024 | 0.062 | 0.0068 | 11.1% | 10.5% |
| 55 | GSIC Center, Tokyo Institute of Technology | TSUBAME-KFC/DL -- Intel Xeon E5-2620-V2, Infiniband FDR | 2,720 | 0.273 | 0.0068 | 2.5% | 1.6% |
| 56 | University of Tuebingen | BinAC -- Intel Xeon E5-2680v4, Infiniband FDR | 4,800 | 0.209 | 0.0063 | 3.0% | 2.2% |
| 57 | The Institute of Atmospheric Physics, Chinese Academy of Sciences | Earth System Numerical Simulator-1 - Intel E5-2680-V3, Infiniband FDR | 24,912 | 0.738 | 0.0063 | 0.8% | 0.6% |
| 58 | Joint Supercomputer Center RAS | MVS-10P - Intel E5-2690, Infiniband FDR, Xeon Phi SE10X | 2,992 | 0.376 | 0.0049 | 1.3% | 0.9% |
| 59 | University of Rijeka | Bura - Bullx Intel E5-2690v3, Infiniband FDR | 5,952 | 0.234 | 0.0047 | 2.0% | 1.6% |
| 60 | CINECA | Galileo - Dual Intel E5-2630 v3 2.4 GHz, Infiniband QDR, Dual NVIDIA K80 | 2,720 | | 0.0046 | | 1.9% |

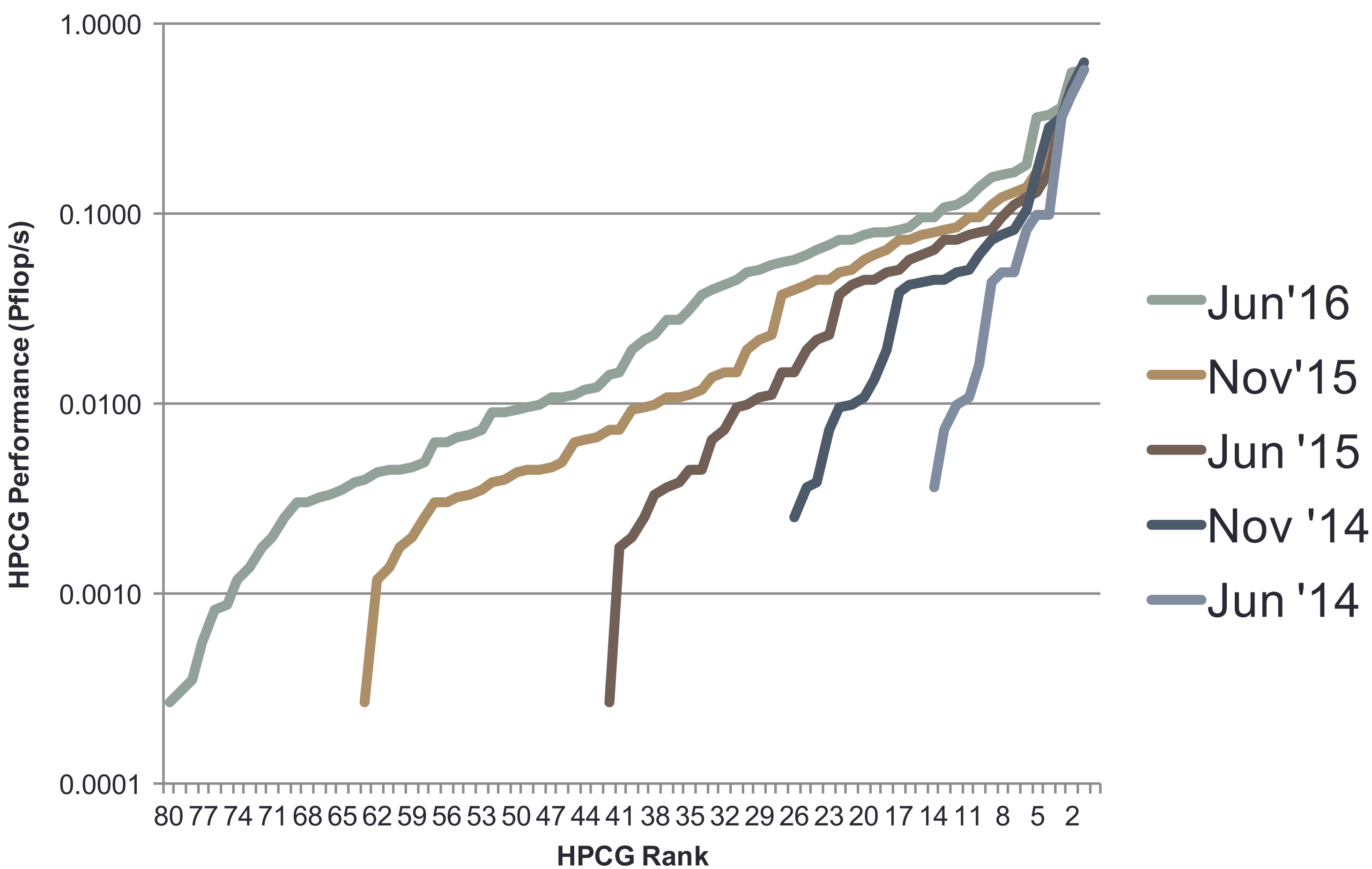
# 61-70

| Rank | Site | Computer | Cores | Rmax | HPCG | HPCG/HPL | % of Peak |
|---|---|---|---|---|---|---|---|
| 61 | NSC / Linkoping | Bifrost - ASUS, Intel Xeon E5-2640v3 8C 2.6GHz, Intel Truescale Infiniband QDR | 10,256 | 0.326 | 0.0045 | 1.4% | 0.8% |
| 62 | Shanghai Supercomputer Center | Magic Cube II - Intel E5-2680-V3, Infiniband EDR | 9,960 | 0.296 | 0.0044 | 1.5% | 1.1% |
| 63 | Max-Planck-Institut für Mikrostrukturphysik | Cruncher - Intel E5-2680-V3, Intel Truescale Infiniband QDR | 12 | 0.112 | 0.0040 | 3.6% | 2.8% |
| 64 | Cambridge University | Wilkes - Dell T620 Cluster, Intel Xeon E5-2630v2 6C 2.600GHz, Infiniband FDR, NVIDIA K20 | 5,120 | 0.240 | 0.0039 | 1.6% | 1.0% |
| 65 | Chelyabinsk | RSC Tornado SUSU, Intel X5680, Infiniband QDR, Xeon Phi SE10X | 4,032 | 0.288 | 0.0036 | 1.2% | 0.8% |
| 66 | CINECA | Galileo - Dual Intel E5-2630 v3 2.4 GHz, Infiniband QDR, Dual Intel Xeon Phi 7120P | 13,600 | | 0.0034 | | 1.5% |
| 67 | Atos Angers | Sid - Bullx Intel E5-2680v3, InfiniBand FDR | 4,224 | 0.129 | 0.0032 | 2.5% | 2.0% |
| 68 | St. Petersburg Polytechnic University | Polytechnic RSC PetaStream - Intel E5-2650 v2, Infiniband FDR, Xeon Phi 5120D | 232 | 0.170 | 0.0031 | 1.8% | 1.2% |
| 69 | Supercomputing Center of Chinese Academy of Sciences | Era-2 - Intel E5-2680-V3, Infiniband FDR, Xeon Phi + NVIDIA K20 | 13560 | 0.407 | 0.0030 | 0.7% | 0.6% |
| 70 | SURFsara | Cartesius - Bullx B515 cluster, Intel Xeon E5-2450v2 8C 2.5GHz, InfiniBand 4x FDR, Nvidia K40m | 3,036 | 0.154 | 0.0025 | 1.7% | 1.2% |

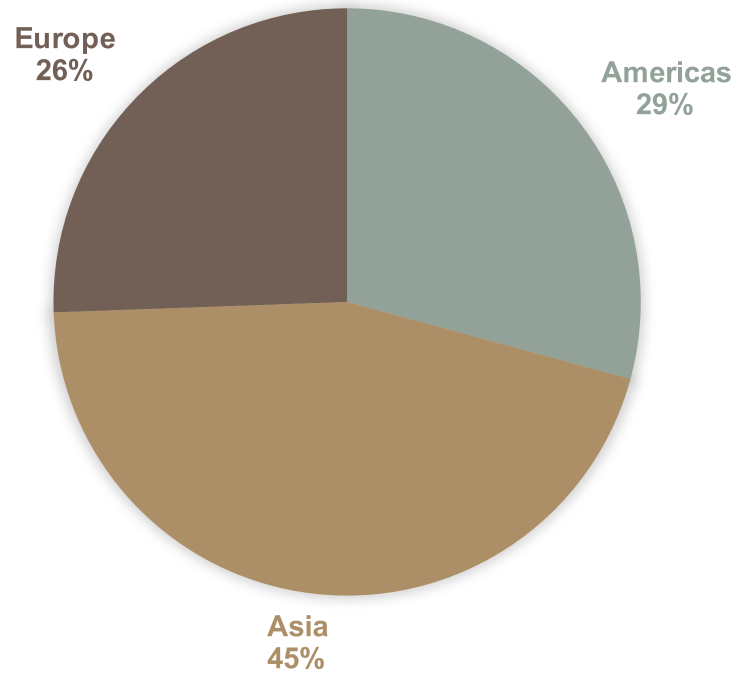
# 71-80

| Rank | Site | Computer | Cores | Rmax | HPCG | HPCG/HPL | % of Peak |
|---|---|---|---|---|---|---|---|
| 71 | CINECA | Galileo - Dual Intel E5-2630 v3 2.4 GHz, Infiniband QDR | 6,400 | | 0.0020 | | 1.6% |
| 72 | Moscow State University / Research Computing Center | Lomonosov - Intel Xeon X5570/X5670/E5630 2.93/2.53 GHz, PowerXCell 8i Infiniband QDR, Dual NVIDIA Fermi 2070 | 78,660 | 0.617 | 0.0017 | 0.3% | 0.2% |
| 73 | IT Services Provider | Aquarius - Intel Xeon E5-2640-V3, Infiniband QDR | 8 | 0.034 | 0.0014 | 4.0% | 3.2% |
| 74 | Joint Supercomputer Center RAS | RSC PetaStream - Intel E5-2667 v2, Infiniband FDR, Intel Xeon Phi 7120D | 3,904 | 0.054 | 0.0012 | 2.2% | 1.5% |
| 75 | Yaqingjie Street 30 | hbemc_2016A -- Intel E5-2680v3, Infiniband FDR | 2,304 | | 0.0009 | | |
| 76 | Hefei City,Anhui Province | YUJING -- Intel Xeon E5-2680v3, custom | 1,440 | 0.001 | 0.0008 | | |
| 77 | No.180 Wusidong Road. Baoding City, Hebei Province,P.R.C | KunYu -- Intel Xeon E5-2680v3, Infiniband FDR | 960 | 0.001 | 0.0006 | | |
| 78 | hongguancun Software Park II, No. 10 West Dongbeiwang Road, Haidian District, Beijing 100193, China | CSRC -- Intel Xeon E5-2680v3, Infiniband FDR | 528 | 0.000 | 0.0004 | | |
| 79 | 18, Xueyuan Road, Haidian District, Beijing,China | geo -- Intel Xeon E5-2680v3, Infiniband FDR | 12 | 0.000 | 0.0003 | | |
| 80 | CINECA | Pico - Dual Intel Xeon E5-2670v2 2.5 GHz, Gigabit Ethernet | 1,200 | | 0.0003 | | 1.1% |

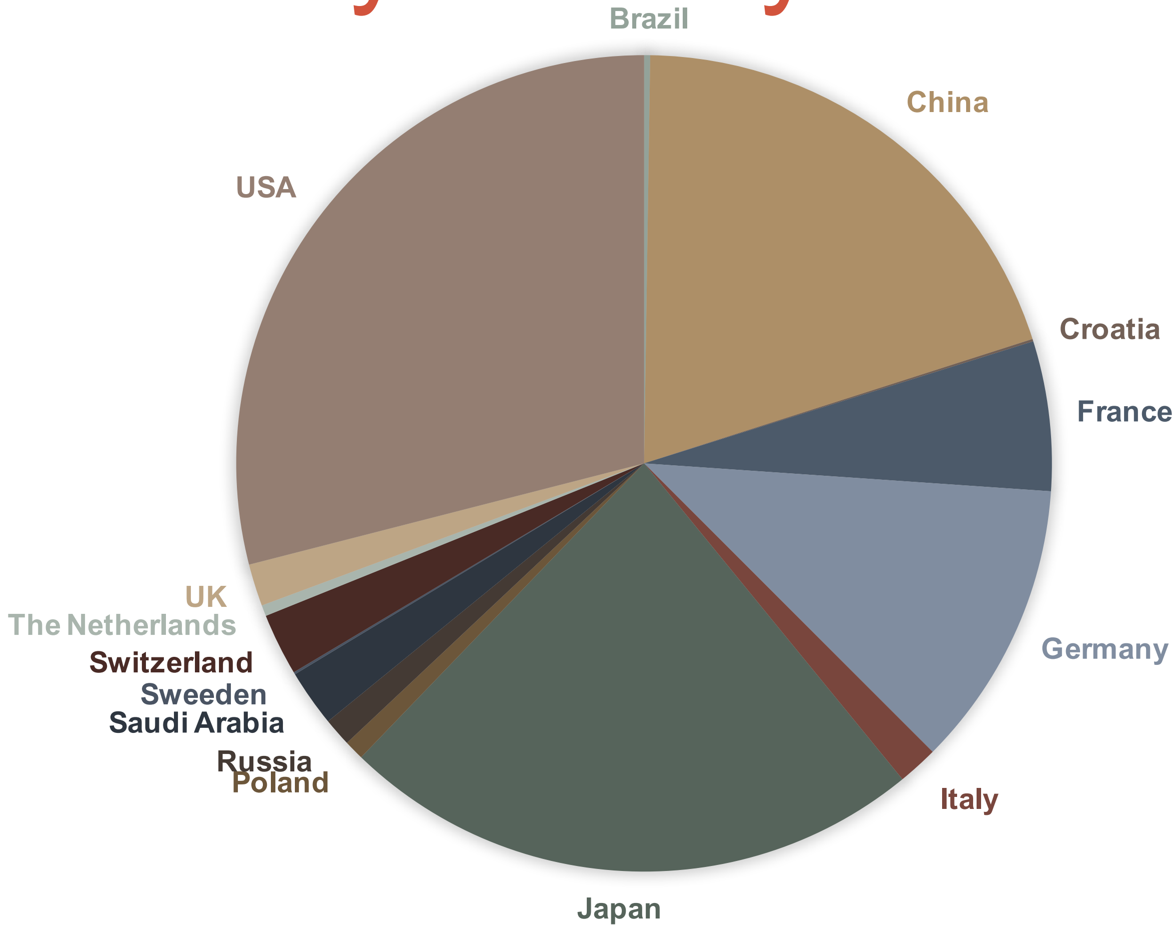
# HPCG Lists Over Time



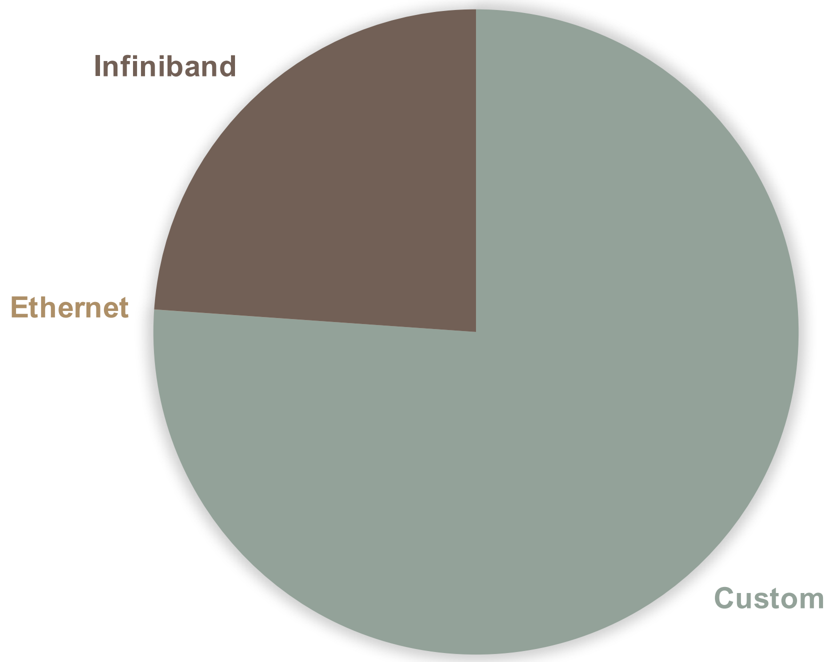
# Performance by Region



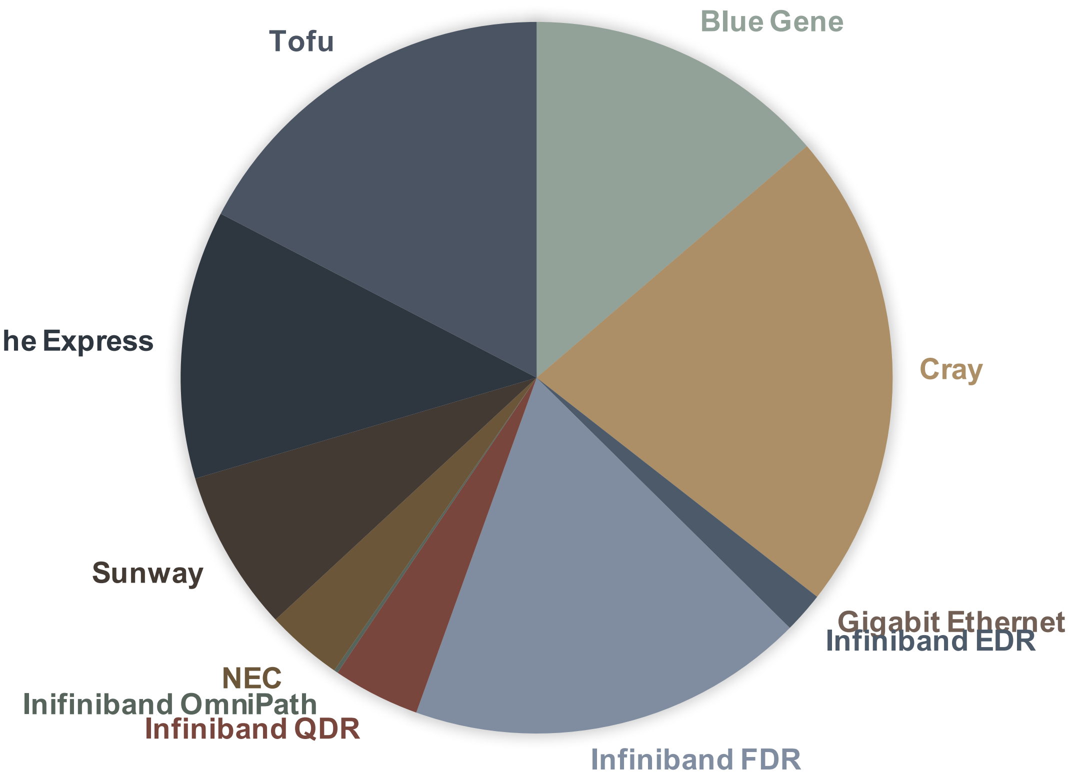
# Performance by Country



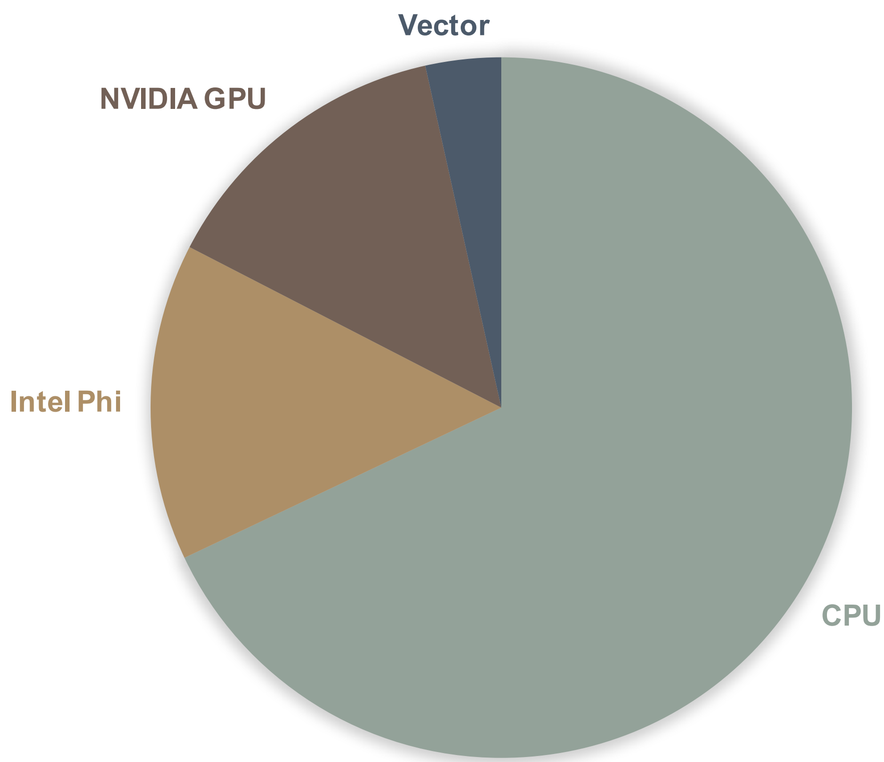
# Performance by Network Type



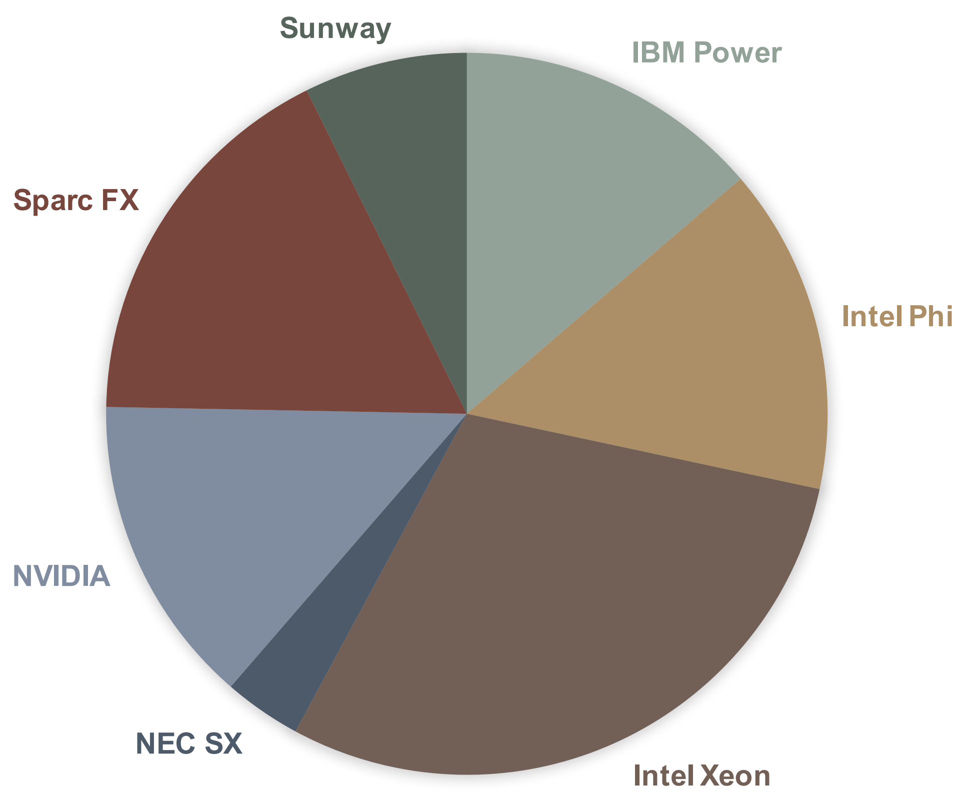
# Performance by Network Details



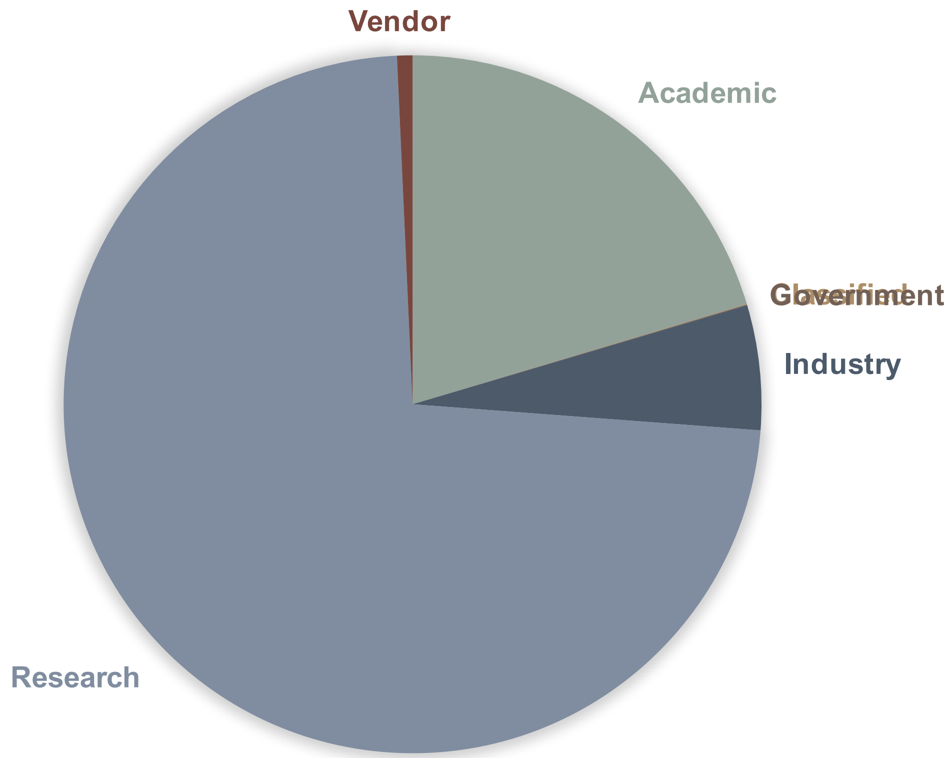
# Performance by Processor Type



# Performance by Processor Detail



# Performance by Segment



# Performance by Integrator