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|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------|----------------------------------------------|
| <b>Institution:</b> The University of Edinburgh                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                                  |                                              |
| <b>Unit of Assessment:</b> UoA 9 - Physics                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |                                  |                                              |
| <b>Title of case study:</b> Particle Physics computations driving the Computing Industry: Intel and IBM high-performance computing and machine learning                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |                                  |                                              |
| <b>Period when the underpinning research was undertaken:</b> 2001–2018                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                                  |                                              |
| <b>Details of staff conducting the underpinning research from the submitting unit:</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                                  |                                              |
| <b>Name(s):</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | <b>Role(s) (e.g. job title):</b> | <b>Period(s) employed by submitting HEI:</b> |
| Prof. Peter Boyle                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | Professor                        | 2000–present                                 |
| Prof. Ken Bowler                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | Professor                        | 1993–2005                                    |
| Prof. Tony Kennedy                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | Professor                        | 1998–present                                 |
| Prof. Richard Kenway                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | Professor                        | 1993–2021                                    |
| Dr Brian Pendleton                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | Senior Lecturer                  | 1993–present                                 |
| Dr Jan Wennekers                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | PDRA                             | 2006–2009                                    |
| Dr James Zanotti                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | Research Fellow                  | 2005–2011                                    |
| <b>Period when the claimed impact occurred:</b> August 2013–December 2020                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                                  |                                              |
| <b>Is this case study continued from a case study submitted in 2014?</b> N                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |                                  |                                              |
| <b>1. Summary of the impact</b><br><p><b>Attribution:</b> Lattice Quantum Chromodynamics research at the University of Edinburgh has underpinned partnerships with IBM and Intel. Professor Peter Boyle co-authored research papers and patents with both companies.</p> <p><b>Impact:</b> Boyle designed part of the central processing unit of IBM's Blue Gene/Q supercomputer. Separately, his work with Intel 1) triggered the release of improved software for the company's Omni-Path Architecture and 2) led to the definition of a new data format — BFloat16 — released on Intel's new 3rd Generation Xeon® Scalable Processors.</p> <p><b>Beneficiaries:</b> IBM, the scientific community, their industrial partners, the United States' National Nuclear Security Administration, Intel, and companies using Intel's 3rd generation processors (Alibaba, Tencent, Baidu, Lenovo, and Hewlett Packard amongst others) and their clients.</p> <p><b>Significance:</b> Blue Gene/Q machines have accelerated simulations across many scientific fields and has contributed to the United States' National Nuclear Security Administration avoiding peacetime nuclear tests during the REF period. The BFloat16 data format speeds up machine learning and its use in Intel's new processors means they are the first mainstream processors to include built-in AI training acceleration.</p> <p><b>Reach:</b> Blue Gene/Q machines have been installed in North America, Europe, Australia, and Japan and were used by researchers tackling problems relating to jet engines, cancer detection, friction-reducing materials, next-generation nuclear reactors, protein design, and concrete. Machine learning spans many sectors of commerce and industry and Intel's new processors are now available in numerous servers and have been adopted by cloud service providers and technology giants.</p> |                                  |                                              |
| <b>2. Underpinning research</b><br><p>Lattice Quantum Chromodynamics (QCD) underpins our understanding of fundamental particles, specifically quarks and gluons. In lattice QCD a lattice is used to define both the quark and gluon fields, which approaches the continuum limit as the lattice spacing decreases. Since the computational cost increases dramatically as the lattice spacing decreases, numerical lattice QCD calculations – typically using Monte Carlo methods – require large supercomputers.</p> <p>Consequently, lattice QCD has been pushing the boundaries of computational science for decades. Academic research on optimized software and hardware solutions is a key driver of scientific advances in this field, and partnerships with industry were driven by the need to meet these scientific challenges. University of Edinburgh (UoE) researchers have been leaders in both lattice QCD research and in the advancement of these software and hardware solutions.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                  |                                              |

**Collaboration with IBM:** From 2001 until 2004 UoE researchers worked with Columbia University and IBM to develop the QCDOC supercomputer, an academic design tailored for Lattice QCD simulations [R1]. A key motivation of this collaboration was to do the lattice QCD research presented in, for example, [R2]. Concurrently, UoE researcher Prof. Peter Boyle developed the BAGEL library [R3], supporting several precision and memory pattern options to allow architecture specific optimisation. This has been a cornerstone of lattice QCD simulations carried out at UoE (e.g., [R4]).

Building on these foundations, UoE researchers were invited to join the IBM team working on the next generation supercomputer, Blue Gene/Q. This was a \$200M project part funded by the US Department of Energy (DoE). Prof. Boyle was invited to lead the design of the cache prefetch engine, the main interface between the computer's processor core and memory system. The work was published in the IBM Journal of Research and Development [R5].

The chip was a 45nm CMOS system-on-chip and the entire design involved around 200 IBM engineers over a period of five years. Boyle designed around 8% of the silicon area of the chip. The R&D phase of the project took place between 2007 and 2012, and the final patents, which include Boyle, were awarded in 2014, 2015, and 2018 and are listed below:

- List based prefetch (2014), Boyle, P. et al. US Patent 8,806,141
- Multi-petascale highly efficient parallel supercomputer (2015), Asaad, S. et al. (including Boyle, P.) US Patent 9,081,501
- Multi-petascale highly efficient parallel supercomputer (2018), Asaad, S. et al. (including Boyle, P.) US Patent 9,971,713

**Collaboration with Intel:** In 2014, Intel's many core architecture directions were identified by Boyle as the most interesting possible replacement for the Blue Gene/Q computer, and the UoE partnered with Intel to form an Intel Parallel Computing Centre. In 2016, this was expanded to a direct collaboration between Columbia, UoE, and Intel, with 2 FTE from the Intel Pathfinding and Architecture Group. The group provided Intel with feedback on several possible architectures and identified software scalability limits for Intel's flagship high-performance computing (HPC) Omni-Path Architecture [R6].

Boyle's work on mixed precision solvers for QCD fuelled a strategic partnership between Intel and the Turing Institute. Two engineers were placed by Intel onsite at the UoE to work with Boyle on the analysis of machine learning workloads. In 2017, this team developed tools and performed a detailed numerical analysis study of the influence of floating point rounding and exponent range on the convergence of machine learning training codes on a wide range of industry standard benchmark problems (e.g., CIFAR, RESNET, MNIST).

Boyle and his team demonstrated that the IEEE fp16 implemented by Nvidia GPU's with 10 mantissa bits and 5 exponent bits is sub-optimal. The team demonstrated that the dynamic range of operands present in typical machine learning problems requires 8 exponent bits. The idea was regarded as commercially valuable and under the terms of the collaboration agreement with Intel, was submitted as an Intel internal Invention Disclosure, since open publication would be prejudicial to patentable intellectual property. Intel's internal review recognised the value of the invention, and journal publication was halted. In 2018, a US Patent Application was made with specific proposed instruction set extensions and documentation of the machine learning numerical analysis improvement.

- FP16-S7E8 Mixed precision for deep learning and other algorithms (2018), Kashyap, S.N., Lepper, A., Boyle, P., US Patent Application 20190042544

### 3. References to the research

[R1] P.A. Boyle, D. Chen, N.H. Christ, et al. 'Overview of the QCDSF and QCDOC computers', IBM Journal of Research and Development, 49, Number 2/3, 351–365 (2005)  
DOI: <https://dx.doi.org/10.1147/rd.492.0351> [43 citations, WoK]

[R2] D.J. Antonio, T. Blum, K.C. Bowler, P.A. Boyle et al. (incl. A. Kennedy, R. Kenway), (RBC Collaboration, UKQCD Collaboration) 'First results from 2+1-flavor domain wall QCD:

*Mass spectrum, topology change, and chiral symmetry with  $L_s=8$* , Phys. Rev. D, 75 114501(2007) DOI: <https://doi.org/10.1103/PhysRevD.75.114501> [34 citations, WoK]

[R3] P.A. Boyle, 'The BAGEL assembler generation library', Computer Physics Communication, 180, 2739-2748 (2009) DOI: <https://doi.org/10.1016/j.cpc.2009.08.010> [42 citations, WoK]

[R4] Y. Aoki, R. Arthur, T. Blum, P.A. Boyle et al. (incl. B. Pendleton, J. Wennekers, J. Zanotti), (RBC Collaboration, UKQCD Collaboration) 'Continuum limit physics from 2+1 flavor domain wall QCD', Phys. Rev. D, 83, 074508 (2011)  
DOI: <https://doi.org/10.1103/PhysRevD.83.074508> [155 citations, WoK]

[R5] Boyle P. A., Christ N. H., and Kim C., 'Co-design of the IBM Blue Gene/Q Level 1 prefetch engine with QCD', IBM journal of research and development, 57, 1-2 (2013) DOI: <https://dx.doi.org/10.1147/JRD.2012.2237149> [2 citations, WoK]

[R6] Boyle P. A., Chuvelev M., Cossu G., Kelly C., Lehner C., and Meadows L., 'Accelerating HPC codes on Intel(R) Omni-Path Architecture networks: From particle physics to Machine Learning', arXiv (2017) <https://arxiv.org/pdf/1711.04883.pdf> [6 citations, GS]

#### 4. Details of the impact

UoE research [R1-5] directly influenced and informed the development of Blue Gene/Q, an IBM supercomputing product that has underpinned scientific and US government workloads throughout the REF period. Boyle's collaboration with Intel produced improved software [R6] and a new data format for machine learning. The latter formed an important component of the new Intel 3rd Generation Xeon® Scalable Processors launched in June 2020. Details of these impacts are described below.

**Impact on high-performance computing:** Blue Gene/Q was IBM's premier supercomputing product and was in operation on scientific workloads across the world throughout the REF impact period, with 17 systems in use in the United States, Germany, Italy, the UK, France, Switzerland, Australia, Japan, and Canada [I1]. Boyle (UoE) was responsible for the "design of a key logic block in the compute chip" and co-designed "an innovative memory prefetch engine" [I2]. This directly contributed to Blue Gene/Q becoming a "massive and worldwide success". As highlighted by the Chief Architect of the Blue Gene platform, "this represents an enormous impact for one QCD researcher" [I2].

**Impact on national computing facilities:** Blue Gene/Q supercomputer systems, Mira and Sequoia, made use of the joint IBM-Edinburgh-Columbia CPU design [R5] and operated at the US DOE facilities at the Argonne and Lawrence Livermore National Laboratories until December 2019 and January 2020, respectively [I3, I4].

Mira, at the Argonne National Laboratory, was used for open research by researchers across the US spanning the biological sciences, chemistry, earth science, energy technologies, engineering, materials science, physics, and mathematics [I3]. These simulations had a diverse range of impacts from jet engines, supernovae, cancer detection, cosmology, LHC analysis, protein design, quantum chemistry, nuclear reactors, and even concrete [I3]. To celebrate Mira's achievements following its decommissioning in December 2019, Argonne released a public testimonial to the science produced with the computer. In total, Mira "delivered nearly 40 billion core-hours to more than 800 projects since its launch in 2012, accelerating breakthroughs in fields ranging from materials science to astrophysics" [I3]. This science was enabled in part, and accelerated, by UoE's silicon design contributions [I2].

Livermore's Sequoia system was the fastest computer in the world when it was introduced in June 2012, and stayed in the top ten through to the end of 2018. When it was decommissioned in January 2020, it was still the 12<sup>th</sup> fastest in the world. The Level-1 prefetch engine design, led by Boyle [R5], was a key performance differentiator as it adaptively prefetches memory in advance of the CPU accesses to reduce the amount of time the processor waits for data.

The significance and success of Sequoia can be measured in terms of avoided nuclear weapons tests. Over 150 US warheads were detonated between 1980 and 1992 but since 1992 there have been no explosions as tests were replaced with simulations. During the REF

impact period, Sequoia *“delivered the required petascale computing capabilities that had become necessary to ensure the continued safety and reliability of the nation's aging nuclear deterrent”* by performing *“the advanced weapons science calculations needed to develop the accurate physics-based models for weapons codes”* and quantifying *“the uncertainties in numerical simulations of nuclear weapons performance”* [14]. Other systems available at the time were not capable of carrying out the simulations needed for these calculations and Sequoia therefore played a central role in the ongoing prevention of peacetime nuclear explosions [14].

15 other large Blue Gene/Q systems (each between 49,152 and 1,572,864 cores) also ran science workloads during the REF impact period, retaining high places in the TOP500 list [15]. This included systems installed in Jülich (Germany) and Cineca (Italy) [15] that provided computer cycles to the European Partnership for Advanced Computing in Europe (PRACE). There was a total of 7 PRACE computer systems at the time. The mission of PRACE was to enable high-impact scientific discovery and engineering research and development across all disciplines to enhance European competitiveness for the benefit of society. The programme made 21,000,000,000 core hours of computing time available to over 688 scientific projects and 56 companies, as well as training over 16,000 scientists from 42 countries [16].

**Impact on Machine Learning:** The ongoing collaboration with Intel has improved machine learning in two ways:

- communication between machines operating in high-performance computing environments is quicker and more efficient.
- a new data format — BFloat16 — has enabled the successful training of machine learning problems that failed with previously available formats.

The UoE-led particle physics-based work that identified software scalability limits for Intel's HPC Omni-Path Architecture [R6] led Intel to release improved software in their MPI product. The company's Senior Director of Enterprise and Government Strategic Planning confirms that *“analysis of scalability limitations for QCD codes on Clusters using Intel's Omni-Path Architecture fabric helped identify performance-blocking root cause issues that led to creation first a proof-of-concept solution that was subsequently included in the Intel Omni-Path Architecture software solution in 2019”* [17]. This refinement improved bandwidth and resulted in a 10-fold increase in processing speed within this HPC environment [18]. This has *“enabled data scientists at the Turing, and the wider world, to manage and analyse massive datasets with greater efficiency”* and Intel confirm that the *“code that this work produced is now shipped as standard in Intel products”* [18].

Boyle's 2017 collaboration with Intel on the floating-point format led to a US Patent submission [19]. The ideas proposed in [19] are included in the AVX512 BFloat16 instruction set extensions adopted by Intel in the Cooperlake architecture of their newest 3rd Generation Xeon® Scalable Processors, launched in June 2020 [110]. UoE analysis was influential in demonstrating the numerical convergence superiority of the BFloat16 format over IEEE FP16 format for machine learning. Intel comment that *“Peter [Boyle] and other members of his team performed research into new numerical methods and data types with lower-precision for Deep Learning training, including use of IEEE FP16 for the weights in several representative Deep Learning networks as well as simulation of the convergence behavior. The research resulted in definition of a new 16-bit floating point data type – BFloat16 – scheduled to be released on Intel processors in 2020. The new data type creates the opportunity for Deep Neural Networks to train on standard CPU hardware”* [17]. BFloat16 support means these processors are the first mainstream processors to offer built-in AI training acceleration [110].

This work accelerates and stabilises convergence of machine learning training across a broad range of applications. It enables a wide range of neural network problems, such as handwriting recognition and image classification, that would otherwise fail to successfully train. Resulting simulations are almost twice as fast [110] and, as Karl Solchenbach, Intel's Director of Exascale Labs Europe, explains: *“If you can do the same calculation with the same accuracy with 16 bits rather than the standard 32 bits, that's great! It saves you half the memory, it makes the calculations much faster, and you can save silicon space in hardware”* [18].

Machine learning is transformative across the modern economy with applications ranging from self-driving cars, through digital assistants, to large-scale automation of repetitive tasks. Facebook have confirmed that Intel's new processors form the basis for its newest Open Compute Platform servers, while other leading cloud service providers such as Alibaba, Baidu and Tencent have also announced their adoption of the processors [I10]. Upgraded servers using the processors have also been released by Lenovo, Supermicro, Hewlett Packard, Inspur, Gigabyte, and Huawei [I11]. AI acceleration, enabled by the BFloat16 data format, is commonly cited as a key feature and illustrates the influence that UoE's work has had on the machine learning hardware market.

Intel is the leading chip maker across the world, and the scope and market penetration of the changes UoE have influenced is large: company revenue is around USD72,000,000,000 (01-2020), and changes have taken place across the product line. The UoE's floating-point proposal is a good alternative to the "flexpoint" proposal by a startup Nervana, who were acquired by Intel in 2016 for over USD400,000,000 (08-2016). UoE's proposal idea won out and this example sets a scale on the commercial value of a good floating-point idea. In *Intel's* own words, the collaboration with the UoE has "*produced significant results and insights that have contributed to Intel's future technology research, product implementation, and application requirements for future architectures ... In summary, the benefits to Intel of the University of Edinburgh collaboration have been many and substantial.*" [I7].

### 5. Sources to corroborate the impact

[I1] Blue Gene/Q supercomputers in TOP500 list in Nov 2013:

<https://www.top500.org/lists/top500/list/2013/11/>

[I2] Support letter from IBM Chief Architect

[I3] Article written by the Argonne National Laboratory on the science performed using Mira:

<https://www.alcf.anl.gov/news/mira-s-enduring-legacy-scientific-computing-advances>

[I4] Lawrence Livermore National Laboratory article on Sequoia: <https://asc.llnl.gov/asc-sequoia>

[I5] 17 Blue Gene/Q machines used for scientific workloads during the REF period (PDF document)

[I6] PRACE in numbers fact sheet: <https://prace-ri.eu/wp-content/uploads/Fact-Sheet-PRACE-in-Numbers.pdf>

[I7] Testimonial from the Intel Senior Director of Enterprise and Government Strategic Planning

[I8] UoE-Turing-Intel case study: <https://www.turing.ac.uk/research/impact-stories/co-designing-computing>

[I9] US Patent Application: 20190042544 [FP16-S7E8 MIXED PRECISION FOR DEEP LEARNING AND OTHER ALGORITHMS](#). P. Boyle, S. Kashyap, A. Lepper

[I10] Launch of new Xeon processors: <https://www.hpcwire.com/2020/06/18/intel-debuts-cooper-lake-xeons-for-4-8-socket-platforms/>

[I11] Press releases announcing upgraded servers:

a) Lenovo: <https://lenovopress.com/lp1366-unique-intel-features-available-with-sr850-v2-sr860-v2#4-intel-optane-persistent-memory-200-series>

b) Supermicro: <https://www.supermicro.com/en/pressreleases/supermicro-launches-4-socket-server-bringing-outstanding-performance-broad-set>

c) Hewlett Packard: <https://community.hpe.com/t5/servers-systems-the-right/introducinghpe-s-new-as-a-service-building-block-for-digital/ba-p/7090403#.X6A0VYj7RPY>

d) Inspur: <https://web.archive.org/web/20201102163707/https://en.inspur.com/en/2490786/2512964/index.html>

e) Gigabyte: <https://www.gigabyte.com/Press/News/1808>

f) Huawei: <https://www.huawei.com/en/news/2020/6/huawei-fusionserver-pro-v6-intel>