Institution: University of Bath

Unit of Assessment: B10 Mathematical Sciences

Title of case study: Changing perspectives on the relevance of mathematics research to the modern world

Period when the underpinning research was undertaken: 2000 - 2020

Details of staff conducting the underpinning research from the submitting unit:		
Name(s): Christopher Budd	**Role(s) (e.g. job title):** Professor of Applied Mathematics	**Period(s) employed by submitting HEI:** September 1995 – present

Period when the claimed impact occurred: 2014 - 2020

Is this case study continued from a case study submitted in 2014? N

1. Summary of the impact

Professor Chris Budd, OBE at University of Bath is a leading researcher applying mathematics to industrial and other problems, and one of the UK mathematicians most actively involved in public engagement. He inspires large, diverse, and international, audiences by using material from his own research communicated in an accessible way to a general audience. By communicating this research to the public via a range of mechanisms, particularly his Gresham Lectures, he has changed the way that his audience views the relevance of mathematics research to their lives. He has trained the next generation of mathematics communicators and teachers through his lectures and frequent masterclasses.

2. Underpinning research

Professor Budd is active in working in applied mathematics, numerical analysis, inverse problems, dynamical systems, with a special emphasis on climate and weather modelling. A major theme of Budd's University of Bath research is in industrial applied mathematics. He collaborates extensively with many companies and advisory bodies including the Knowledge Transfer Network, BT, the Met Office, Aviva, Seiche, PepsiCo, Airbus, Syngenta, Schlumberger, Unilever, and recently with Scientific Pandemic Influenza Group on Modelling (SPI-M). He has worked on a wide variety of problems with these companies, applying deep mathematical theory (in particular, in the areas of nonlinear systems, partial differential and numerical analysis) to find their solution. His co-creation of knowledge in mathematical modelling and its theory and applications, has provided a rich resource of examples for his extensive work in public engagement.

He presents material which is directly related to his own research to diverse audiences, especially highlighting the many applications of mathematics. This makes his lectures and articles interesting and relevant. His main research programme (RP), and some key papers, from which his Public Engagement work draws material, are as follows:

RP1. Climate and weather. In an ongoing, and close, collaboration with the Met Office, Budd has carried out extensive research in the mathematical and numerical modelling of weather (both atmospheric and space weather) and climate systems **[R1]**, and in developing new adaptive moving mesh numerical methods (based on ideas in optimal transport) for solving these models **[R2]**, **[R3]** (both co-authored with the Met Office). See also [I], which states:

"…collaboration that led to significant improvements in the computational efficiency of the data assimilation system through application of the multi-grid approach as well as highly novel moving-mesh techniques".

RP2. Dynamical systems. He has co-authored a major textbook **[R4]** on (non-smooth) dynamical systems and predictability, which introduced many new ideas about novel bifurcations which occur when smoothness restrictions are relaxed. He has applied the results to give much greater understanding of models of climate (especially the ice ages), geological folding, and power generation (involving switched systems). More recent work with the National Grid combines both areas of research studying the impact of climate change on energy networks.

RP3. Inverse problems and data assimilation. He has developed new tools for data assimilation, and for image processing. They take novel ideas for regularisation, coupled to adaptivity and new error estimates, to deliver much improved solution reconstructions **[R5]**. These methods have been used for weather forecasting, for tomographic reconstructions, for land mine detection, and also by Seiche Ltd. for the detection of whales underwater.

RP4. Mathematical modelling using non-linear partial differential equations (PDEs). He has conducted extensive research in mathematical modelling and in the analysis of nonlinear PDEs. Part of this work has been in the mathematics of food, looking at the mathematical modelling of food production, freezing, and cooking **[R6]**. He collaborates with PepsiCo on crisp manufacture modelled through fourth-order PDEs, Mondelez/Nigerian Cocoa institute on cocoa production, modelled using differential-delay equations, and the Chipping Camden and Chorleywood Food Research Association (CCFRA) on safe microwave cooking modelled by solving Maxwell's equations in complex media.

3. References to the research

[R1] Morupisi, KS & Budd, C 2021, 'An analysis of the periodically forced PP04 climate model, using the theory of non-smooth dynamical systems', *IMA Journal of Applied Mathematics*, vol. 86, no. 1, pp. 76-120. https://doi.org/10.1093/imamat/hxaa039 (Published 14 October 2020)

[R2] Budd, CJ, Cullen, MJP & Walsh, EJ 2013, 'Monge–Ampére based moving mesh methods for numerical weather prediction, with applications to the Eady problem', *Journal of Computational Physics*, vol. 236, pp. 247-270. https://doi.org/10.1016/j.jcp.2012.11.014

[R3] Cook, SP, Budd, C, Melvin, T 2019, 'The moving mesh semi-Lagrangian MMSISL method', *Journal of Computational Physics*, vol. 393, pp. 484-502. https://doi.org/10.1016/j.jcp.2019.01.037

[R4] di Bernardo, M, Budd, CJ, Champneys, AR & Kowalczyk, P 2008, Piecewise-smooth dynamical systems: theory and applications. *Applied Mathematical Sciences*, vol. 163, Springer, London, U. K. https://doi.org/10.1007/978-1-84628-708-4

[R5] Budd, C, Freitag, MA & Nichols, NK 2011, 'Regularization techniques for ill-posed inverse problems in data assimilation', *Computers and Fluids*, vol. 46, no. 1, pp. 168-173. https://doi.org/10.1016/j.compfluid.2010.10.002

[R6] Budd, CJ & Hill, ADC 2011, 'A comparison of models and methods for simulating the microwave heating of moist foodstuffs', *International Journal of Heat and Mass Transfer*, vol. 54, no. 4, pp. 807-817. https://doi.org/10.1016/j.ijheatmasstransfer.2010.10.022

4. Details of the impact

Professor Budd pursues a programme of research informed public engagement using a wide range of mechanisms to engage with large audiences. This has stimulated widespread interest in mathematics research, and has inspired the next generation of mathematicians, mathematics teachers, and scientific communicators. Amongst many international prizes for this work (including the 2020 JPBM Communications Award), Budd was awarded an OBE in 2015. Citing this the LMS President said [A]:

> *"Budd is an exemplar for his tireless efforts to bridge the communication gap between state-of-the-art mathematical sciences and the wider public".*

In 2016, Budd was competitively appointed to a 4-year term as Gresham Professor of Geometry [B] and has delivered 24 one-hour public lectures on subjects showcasing many areas of mathematics research. Lectures underpinned by Budd's research include:

RP1. *Climate and weather*
- The mathematics of climate change, 13 November 2018
- The maths of future computing, 8 October 2019

RP2. *Dynamical Systems*
- The energetic mathematician: maths and the power industry, 25 April 2017
- Can maths predict the future? 9 October 2018

RP3. *Inverse problems and data assimilation.*
- The challenge of big data, 15 November 2016
- How maths can save your life: medical imaging, 17 October 2017
- Can maths save the whales and cure cancer? 7 January 2020

RP4. *Mathematical modelling using non-linear PDEs*
- How much maths can you eat: maths of food, 14 February 2017
- Mathematical materials 14 March 2017

The lectures typically attract live audiences of around 200 professionals and sixth-form students, and online international views in the tens/hundreds of thousands. A 20-page summary and video recordings of each, are uploaded on Gresham College's webpage and YouTube. The lectures are assessed by questionnaires of the attendees and feedback from these shows increased awareness, understanding and changed behaviours [C]. From the 2020 series survey (98 responses), when asked if they had done anything new after attending the lectures,

- 38% had a conversation about maths
- 40% looked up a maths topic on the internet
- 22% read an article on maths
- 18% brought someone new to the lectures.

The Gresham College Provost [C] highlights the positive audience impact:

> *"It was fabulous! Good balance between being intellectual and accessible".*
> *"Encouragement to resuscitate my maths and get involved in climate change theory".*
> *"Great info to tell students how maths is useful to real life".*

The lectures led to many speaking invitations, e.g. **New Scientist Instant Expert** 2018, **Heidelberg Laureate Forum** 2019, **New Scientist Live** 2019 (100,000 participants), **Malvern Science Festival** 2020.

Budd writes related monthly articles for *PLUS Maths magazine* (part of the Millennium Mathematics Project at the University of Cambridge). The editor of *Plus Maths* states [D]:

"Since August 2013 the Plus articles you have authored have attracted a total of well over 630,000 unique page views from our international audience … the number of comments posted demonstrate that you have enabled a large number of Plus readers to actively engage with your research/content".

The lectures have been translated into other languages, and together with other outreach work by Budd, have stimulated the creation of STEM events, and changes in the perceptions of mathematics, in other countries. The director of the Italian **FermHAmente** Festival (10,000 attendees) said [E]:

"your work helped inspire me to run FermHAmente science festival, now in its fourth edition, and it had a great impact on its structure and public engagement strategies".

The lecture *Can maths predict the future?* led to Budd acting as a **consultant for a BBC** internet article on *Fractals* with over 127,000 views.

By December 2020, the lecture *The Mathematics of Climate Change* had been viewed over 128,000 times [F], *"The Mathematics of Climate Change…[received] an outstanding number of views. There was a definite spike in views during the Extinction Rebellion protests in 2019"* [G]. Extracts were published in the *Aviva Investor's 2019 Little Book of Data,* distributed to 10,000 of their clients including many senior decision makers. Aviva say: *"From a communications perspective Budd's work is hugely valuable. It sets out complex modelling issues with such clarity"* [H]. The lecture reflects Budd's impact on the operational work of the *Met Office* and in changing public perceptions about weather forecasting. A Met Office Principal Fellow states: *"You are a staunch advocate of the work of the Met Office"* [I].

Budd gets 100s of mailings from teachers and their students showing impact on teaching and learning. For example, a St. Bede's schoolteacher wrote [J]:

"There's a group of 6th form pupils that meet one evening a week where they watch the Gresham College lectures - so they've picked up all of yours. I also have a habit of watching some that you've done and modifying them as starter activity".

Since 2000, Budd has been Prof of Mathematics at the **Royal Institution** playing a leading role in delivering their programme of Secondary Mathematics Masterclasses using topics based on his research. Since August 2013 he has directly reached 3,500 pupils, 350 teachers, and has trained 175 Royal Institution tutors. A teacher blogged [K]:

"The areas he had laid out were all interesting and calculated to inspire interest in mathematical applications or made explicit the mathematics around us".

Sustained impact of Budd's Gresham lectures will follow on from a recently signed book contract in November 2020 with World Scientific Press, and from STEM learning who will use extracts for their teaching materials.

5. Sources to corroborate the impact

[A] Birthday Honours Citation from the LMS president in the LMS Bulletin, July 2015.

[B] Gresham College's webpage on Budd as Prof. of Geometry, accessed 19 January 2021. https://www.gresham.ac.uk/professors-and-speakers/professor-chris-budd/

[C] Letter from the Provost of Gresham College,22 February 2019 citing the results of Gresham's surveys on Budd's Gresham Lectures.

[D] Testimonial from the editor of Plus Maths Magazine, 27 November 2020.

[E] Testimonial from the director of the FermHAmente Festival, Italy, November 2020.

[F] YouTube: the mathematics of climate change,22 November 2018, showing both the number of hits and the large debate that has ensued following the lecture: https://www.youtube.com/watch?v=w4O4jK-lZrl

[G] Gresham College Academic Board, 17 October 2019, Papers D and E.

[H] Letter from Aviva Investors,9 June 2020, describing the impact of Budd's work on their Little Book of Data - "visual vignettes to help us better understand the world and provoke thought", published 2 December 2019. https://www.avivainvestors.com/en-gb/views/aiq-investment-thinking/2019/11/little-book-of-data/.

[I] Testimonial from   Principal Fellow at the Met Office showing the impact of Budd's work on both the operations of the Met Office and on the public perception of weather forecasting research, 23 March 2020.

[J] Letter from a mathematics teacher at St. Bede's College, 25 November 2020.

[K] Teachers blog, 27 April 2019. http://teachingmathsscholars.org/royalinstitutionsupervisit-professorchrisbuddworkshop