Institution: University of Cambridge

Unit of Assessment: 11

Title of case study: Raspberry Pi: the third best-selling computer of all time and the making of a global community of young digital makers and educators

Period when the underpinning research was undertaken: 2000-2020

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Rob Mullins	Reader	Oct 2000 to present
Alan Mycroft	Professor	Oct 1993 to present
Eben Upton	Director of Studies	Oct 2004 to 31 Sep 2007
Jack Lang	Affiliated Lecturer	Apr 1999 to present

Period when the claimed impact occurred: 1 August 2013 - 31 July 2020

Is this case study continued from a case study submitted in 2014? No

Summary of the impact (indicative maximum 100 words)
A team in the Department of Computer Science and Technology at the University of Cambridge have created a new class of affordable computer, the Raspberry Pi, which has become a leading platform worldwide in both educational and industrial settings. The impact includes:

- selling 30 million Raspberry Pi computers at 35USD per piece, creating a market worth over USD1 billion (and more in peripherals), the profits of which go to the Raspberry Pi Foundation for educational purposes. The Raspberry Pi has also created over 230 jobs, both within the Raspberry Pi Foundation Ltd and at the Sony Factory in Pencoed**,** Wales.
- establishing a highly engaged international community for young people and computing enthusiasts through the development of online resources, coding clubs, programmes and competitions which have reached millions of people across over 100 countries worldwide, as well as supporting new training for thousands of computer science teachers in schools.
- creating a whole new class of computing device, transforming the way engineers design control systems in industry, and becoming a standard component of intelligent interfacing.

2. Underpinning research (indicative maximum 500 words)
The Department of Computer Science and Technology at the University of Cambridge (the Department) has a long tradition of research in computer design, from complete machines such as the Titan (1963) and CAP (1976) computers, through early networked servers based on Motorola 68000 on the Cambridge Distributed Computing System (1981), to experimental low-power computer architectures for embedded processors (e.g. JMA: The Java-Multithreading Architecture for Embedded Processors, 2002).

The Raspberry Pi computer [R1] was the product of an experiment in hardware design and its application to education, born of the vision and skill of a group of experts in computer architecture, hardware design and manufacturing in the Department. The project tackled two problems: the falling numbers and quality of students applying to study Computer Science at the University of Cambridge, and the desire to give young people access to programmable hardware at a lower price. The original (modest) aim of the project was to produce 10,000 units of a powerful low-cost (sub USD25) single-board computer to engage young students thinking of applying to Computer Science degrees. The experiment was wildly more successful than anticipated and has transformed the world of digital making and computing education.

Designing a low-cost, high-functioning general-purpose computer required both expertise and vision founded on current trends in technology, education and manufacturing. Different design

concepts were developed informally at the University of Cambridge from 2006, and in 2008 a breakthrough came with the realisation that a new Broadcom System-on-a-Chip (SoC), designed for media-processing applications, could be re-purposed as the heart of a credit-card sized single board computer, capable of running Linux and Python, with a retail cost below USD25. At this point, in November 2008, the design team came together formally as the Raspberry Pi Foundation, with the strong and continuing support of Cambridge University and the Department of Computer Science and Technology. It then took four years to research, design and develop the concept through to the initial manufacturing stage, with the first release in 2012.

The team consisted of University of Cambridge computer scientists and engineers, alongside manufacturing entrepreneurs, who together had the expertise and vision to tackle the problems that they had identified.

From the University of Cambridge Department of Computer Science and Technology:
- Professor Alan Mycroft, bringing deep background in teaching, and research on programming languages, software engineering and algorithms [R2];
- Dr Robert Mullins, whose research included computer architecture, microprocessors, and power consumption [R3;R6];
- Dr Eben Upton, enthusiast for low-cost computing, expert in compiler technology and system-on-chip design [R4]; and
- Jack Lang, a serial entrepreneur and business angel with high-tech and internet companies based in Cambridge, and lecturer in Business Studies for the Department's Computer Science course [R5].

The team from the University were complemented by two colleagues from the wider industry to form the Raspberry Pi Foundation:
- David Braben, CEO of Frontier Developments and author of Elite for the BBC Micro-computer; and
- Pete Lomas, Director of Systems Engineering at Norcott Technologies, an electronic design consultancy.

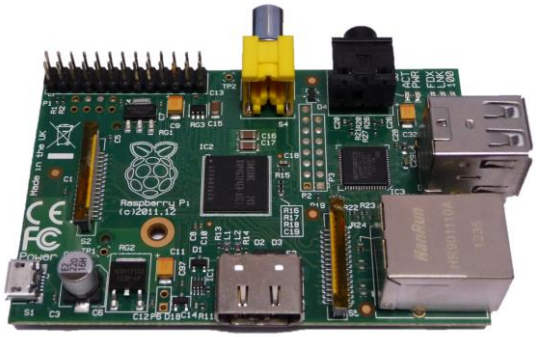
Before the Raspberry Pi, no one had produced a low-cost board that was able to run an operating system like Linux. The team's working hypothesis was that ownership of an accessible and low-cost device was significant, as it would enable a wider audience (both on the age and socio-economic spectrum) to get involved with learning the building blocks of computing. This democratising drive was one of the team's key motivations. The team also recognised the need for their computer to interface with the real world to help engage a broader community and demonstrate to young learners that computers are key to solving real-world problems (rather than abstract ideas that many computer courses focus on).

The apparent simplicity of the Raspberry Pi belies the complexity of the engineering challenge. Designing a low cost computer, without sacrificing size, functionality or reliability, was a huge task. In order to maximise its applications, the Raspberry Pi had to have video and audio capabilities and a wide range of inputs and outputs (such as USB and HDMI). Raspberry Pi also featured general purpose input/output (GPIO) for the direct control of simple hardware extensions. This required highly innovative computer chip and software design to limit the system's power consumption and thermal stability while performing such intensive tasks. The team's design was eventually realised with just 3 chips, an ARM-based media processing SoC from Broadcom, a networking chip from SMSC (USB and Ethernet), and the DRAM. The resulting board had a price low enough for a school or university to give it to each student. With the addition of a low-cost keyboard and a TV for display, it can act as a fully functional programmable computer. It can be networked and used in groups for more advanced students or for industry use.

The Raspberry Pi won the INDEX Design Award on 29 August 2013, and in June 2017 it won the MacRoberts Award, the UK's longest running and most prestigious prize for engineering innovation, presented by the Royal Academy of Engineering.

3. References to the research (indicative maximum of six references)
All research outputs marked with * have been through a rigorous peer-review process.

[R1]. The Raspberry Pi computer. Winner of the INDEX Design Award (2013), and MacRoberts Award (2017), the UK's longest running and most prestigious prize for engineering innovation, presented by the Royal Academy of Engineering. Dr Dame Sue Ion, Chair of the MacRobert Award judging panel, said of the Raspberry Pi: 'By blending older and newer technologies with innovative systems engineering and circuit board design, the team has created a computer that is cheap, robust, small and flexible'. Image shows Raspberry Pi Model B from November 2012, bought for GBP21.60+VAT



*** [R2]** Jonathan J. Davies, Alastair R. Beresford, Alan Mycroft: "Language-Based Optimisation of Sensor-Driven Distributed Computing Applications", 11th International conference on Fundamental Approaches to Software Engineering, FASE 2008: 407-422 DOI: https://doi.org/10.1007/978-3-540-78743-3_30

*** [R3]** Robert Mullins, Simon Moore: "Demystifying data-driven and pausible clocking schemes", 13th IEEE International Symposium on Asynchronous Circuits and Systems (ASYNC'07) DOI: https://doi.org/10.1109/ASYNC.2007.15

*** [R4]** Eleanor Toye, Richard Sharp, Anil Madhavapeddy, David Scott, Eben Upton & Alan Blackwell: "Interacting with mobile services: an evaluation of camera-phones and visual tags", Pers Ubiquit Comput 11, 97–106 (2007) DOI: https://doi.org/10.1007/s00779-006-0064-9

[R5]. J. Lang, "High-Tech Entrepreneur's Handbook: How to Start & Run a High-Tech Company", Financial Times Management, 2002. ISBN 0273656155

*** [R6]** Arnab Banerjee, Robert Mullins, Simon Moore: "A Power and Energy Exploration of Network-on-Chip Architectures", First International Symposium on Networks-on-Chip (NOCS'07) DOI: https://doi.org/10.1109/NOCS.2007.6

4. Details of the impact (indicative maximum 750 words)
In 2017, MacRoberts Award Judge Dr Frances Saunders announced that "the Raspberry Pi team has achieved something that mainstream multinational computer companies and leading processing chip designers not only failed to do, but failed even to spot a need for" [E1]. With a small team, "Raspberry Pi has redefined home computing for many thousands of people across the world, even taking 1% of the global PC market" and their "highly innovative design...has taken the education and maker market by storm" [E1].

Impact 1: Raspberry Pi has manufactured and sold over 30 million Raspberry Pi computers as well as creating over 230 jobs and a market worth over USD1 billion. The Raspberry Pi is the "third best-selling general-purpose computer of all time" [E2] with 30 million being sold by the end of 2019 [E2]. In 2019 Raspberry Pi (Trading) Limited had a trading income of GBP39 million, generating a surplus of GBP5 million [E3]. Manufacturing the Raspberry Pi has created jobs both within the Foundation itself and at Sony UK TEC in Pencoed**,** South Wales, where the computer is made. The charitable Foundation employs well over 100 people, the wholly owned Raspberry Pi Trading Ltd employs 50, and over 80 people are employed on Raspberry Pi at the Sony Factory. Sony UK TEC managing director Steve Dalton said that 2012-2017 had seen "the unprecedented growth across our Pencoed facility…that was intrinsically linked to the success of the Raspberry Pi" [E4].

Impact 2: Raspberry Pi has established an international educational community for young people and computing enthusiasts, and has been used in training computer science teachers. The profits generated from the Raspberry Pi Foundation's commercial activities are used to fuel its wider educational mission; including online resources, coding clubs, programmes, competitions and training for educators. As the Chair of the MacRobert Award judging panel explains, the success of its sales means that the Raspberry Pi Foundation now represents a large, sustained global effort to help "multiple generations to get into coding" and "communities in the developing world are also being empowered by the Raspberry Pi and its modern day computing-on-a-budget" [E5]. As of 2019, the Raspberry Pi Press published six magazines which are downloaded by over 200,000 people every month, and which together have 10,000 print subscribers [E3]. The 2018 Annual Report notes that 3.5 million people learned through Raspberry Pi's 220 online projects that year alone [E6], whilst offline community events include Raspberry Jams: independently organised community events and workshops about digital making with Raspberry Pi. The reach of this impact increased when the Raspberry Pi Foundation merged with *Code Club* in 2015 and the *CoderDojo Foundation* in 2017 (see [E6] for figures in table below).

Community Event	Geographical Reach	Number of People Reached
Raspberry Jams 2018	54 countries	21,000 young people reached
Code Club 2018 (9-13 year olds)	Global	250,000 young people reached
Coder Dojo Foundation 2018 (7-17 year olds)	114 countries	55,000 young people reached

With the help of a GBP100,000 donation from Google [E7], the network of *Code Clubs* has grown by 41% with over 17,000 educators and volunteers running them [E6]. When asked, 92% of these educators agreed that the young people at their club have improved their programming skills since starting, and 88% agree that the young people are more confident in their computer skills [E6]. There are over 12,000 educators and volunteers running *Coder Dojos* [E6] and 86% agree that the young attendees are more interested in programming and computers since they started, with 84% saying that the young people they reach have improved their programming skills [E8].

The Raspberry Pi Foundation is also investing in teachers and developing new training resources for teaching computer science in schools. A 2017 report by the Royal Society highlighted the small number of Key Stage 4 pupils taking GCSE computer science (only 11% in 2017 [E9]) and the lack of support and training of teachers. Raspberry Pi is tackling these issues through their *Picademy* scheme which includes residential training events and membership of a community of digital making practitioners. In 2019 there were 2,400 certified educators with 360 newly trained that year [E3]. These educators value their *Picademy* training and perceive it to have greatly improved their knowledge and skills in computing as well as their confidence in teaching physical computing [E8]. 15 new online courses aimed at teachers were created in 2019, with 30,000 people participating, of which 78% agree that they had improved their computing skills [E3].

Impact 3: the Raspberry Pi has created a new class of computing device that has revolutionised how engineers design control systems in industry, and it has become a standard component of intelligent-interfacing. The MacRobert Award judging panel said of the Raspberry Pi: 'By blending older and newer technologies with innovative systems engineering and circuit board design, the team has created a computer that is cheap, robust, small and flexible' [E5]; this means that "the micro PC can be used as the control centre of just about anything, from creating video games to robots, multi-room sound systems, pet feeders, or even scientific experiments" [E1].

For example, Hilscher (a global specialist in network connectivity products for device makers, OEMs and end-user manufacturers) produces a netPI industrialized Raspberry Pi 3 B platform - which is housed in an industrial-grade enclosure with a low-emission board design - for connection

to real-time industrial networks. In a recent announcement, Hilscher noted that "sales of the netPI, initially released two years ago, have far exceeded expectations, as automation professionals spot opportunities [for Raspberry Pi] in industry" [E10]. The company says that "today engineers and major end users are jumping at the chance to deploy netPI 3 systems", and that "customers are using netPI at the heart of open-edge connectivity systems in Industrial Internet of Things and Industry 4.0 applications" [E10].

An example of its use in intelligent-interfacing is the testing of 3D-printed stents in the medical arena. In 2017, the Harvard Medical Faculty created a smart stent-testing robot controlled by a Raspberry Pi [E11]. The robot uses machine vision to stop testing at the moment of failure, allowing the team to check which part failed and view a time-lapse leading up to the failure. They commented that "it was remarkably accurate, and given this was done on an academic budget, the Raspberry Pi gave us high-performance multi-core capabilities for very little money" [E11].

5. Sources to corroborate the impact (indicative maximum of 10 references)

[E1] "MacRobert Award 2017 finalists announced", 1 June 2017, Royal Academy of Engineering: https://www.raeng.org.uk/news/news-releases/2017/june/macrobert-award-2017-finalists-announced
[E2] Collated document - Raspberry Pi Sales (see pages 2 and 8 of PDF):
- E3A: "Sales soar and Raspberry Pi beats Commodore 64": https://magpi.raspberrypi.org/articles/raspberry-pi-sales
- E3B: Tweet from Dr Eben Upton, CEO Raspberry Pi Trading Ltd, 14 Dec 2019: https://twitter.com/EbenUpton/status/1205906969443393537

[E3] Raspberry Pi Foundation Report 2019 (see pages 4, 5, 26, 35 of PDF) https://static.raspberrypi.org/files/about/RaspberryPiFoundationReport2019.pdf
[E4] How the iconic Raspberry Pi computer has been given a new lease of life in Wales (see pages 2 and 3 of PDF): https://www.walesonline.co.uk/business/business-news/staggering-10-million-raspberry-pi-13384529
[E5] "The coding revolution marches on: Raspberry Pi wins UK's top engineering innovation prize," 30 June 2017, Royal Academy of Engineering: https://www.raeng.org.uk/news/news-releases/2017/june/the-coding-revolution-marches-on-raspberry-pi-wins
[E6] Raspberry Pi Foundation Annual Review 2018 (see pages 17, 18, 29, 33 of PDF) https://static.raspberrypi.org/files/about/RaspberryPiFoundationReview2018.pdf
[E7] Google's AlphaGo donation will help Code Club grow: https://www.raspberrypi.org/blog/googles-alphago-donation-help-code-club-grow/
[E8] Collated document - Raspberry Pi Annual Reports 2018 for Code Club, Code Dojo and Picademy (see pages 5, 6, 16, 32, 33, 72, 73 of PDF)
- E8A: Code Club Annual Survey 2018 Report: https://www.raspberrypi.org/app/uploads/2019/03/Code-Club-Annual-Survey-2018-1.pdf
- E8B: Coder Dojo Annual Survey 2018 Report : https://www.raspberrypi.org/app/uploads/2019/04/CoderDojo-Annual-Survey-2018.pdf
- E8C: Raspberry Pi Certified Educators: Embedding Picademy Learning in Schools: https://www.raspberrypi.org/app/uploads/2018/08/Embedding-Picademy-learning-in-schools.pdf

[E9] Computing Education in UK Schools – Royal Society report (See page 12). https://royalsociety.org/-/media/policy/projects/computing-education/computing-education-report.pdf
[E10] "Is Raspberry Pi Ready for Industry?" (See pages 2 and 3 of PDF) https://www.automationworld.com/products/control/blog/13319680/is-raspberry-pi-ready-for-industry
[E11] Stent-testing smart robot makes the medical grade (See pages 1, 2 and 3 of PDF) https://www.raspberrypi.org/blog/stent-testing-robot/