Institution: University College London		
Unit of Assessment: 5 Biological Sciences		
Title of case study: The Vital Question: shaping public understanding of astrobiology		
Period when the underpinning research was undertaken:		
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:**
Nick Lane	Professor of Evolutionary Biochemistry	2009 – present
Period when the claimed impact occurred: 2015 - 2020		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact (indicative maximum 100 words)

Professor Nick Lane (UCL Genetics Evolution and Environment) published his highly regarded popular science book, *The Vital Question*, in 2015, based on his pioneering research on energy flow in evolution, stretching from the origin of life to the diseases of old age. The book has changed public and media perceptions about the probability and nature of life in the universe, and its impact has been amplified through ensuing high-profile public engagement work on films, TV and radio programmes. *The Vital Question* has directly shaped science funding, notably the NASA Icy Moons programme and the USD 4,000,000,000 Europa Clipper Mission.

2. Underpinning research (indicative maximum 500 words)

Lane's research examines the role of energy flow in structuring evolution. For decades, research on evolution has been grounded in genes and information, using phylogenetic analyses to understand the tree of life. Yet the evolutionary trajectory of life on Earth does not correspond to genetic information: bacteria have explored far more sequence space than complex (eukaryotic) cells, but never evolved equivalent complexity at the level of cells, organisms or genomes – there are no plants or animals composed of bacterial cells, despite their great genetic versatility. Lane's research explores the deep constraints imposed on all life by membrane bioenergetics, from their postulated origin in structured geological environments (such as hydrothermal vents) to a singular endosymbiosis between two prokaryotes that gave rise to the first eukaryotes, to the fundamental implications of the requirement for eukaryotic cells to maintain two unequal genomes, nuclear and mitochondrial. Lane's work has challenged the gene-centric view of evolution and medicine through rigorous experimental and computational methods that elucidate the constraints that energy flow places on genes, with implications ranging from the search for life in space to age-related disease.

Using this pioneering bioenergetic perspective, Lane's underpinning research has focused on (i) the origin of life, (ii) the emergence of complex cells and (iii) traits shared by all complex life, such as sex and ageing. These research themes are outlined below, citing a selection of Lane's primary papers that represent the research underpinning the ideas synthesized in *The Vital Question*.

(i) **The origin of life**. Lane won the UCL Provost's Venture Research Prize for transformative research in 2009, which enabled him to lead research on the origin of life across three faculties at UCL through the UCL Research Frontiers Origins of Life Initiative, and later the UCL Centre for Life's Origins and Evolution (CLOE). Lane's research has explored the parallels between the membranes of ancient bacteria and archaea and the inorganic pores in hydrothermal systems, where proton gradients across inorganic barriers drive CO_2 fixation

and growth, giving a new perspective on the origin of cells [R1]. Lane's group has developed mathematical models

(ii) **Evolution of complex cells**. Lane's hypothesis paper on the energetics of genome complexity, based on an analysis of energy per gene [R4], has stimulated much discussion in the academic literature, including papers and articles in *eLife*, *PNAS* and *Current Biology*. Lane's theoretical modelling work in collaboration with Professor Andrew Pomiankowski and CoMPLEX (the UCL Centre for Maths and Physics in the Life Sciences and Experimental Biology) has used rigorous mathematical approaches to explore major transitions in evolution. These range from the origin of the genetic code to the evolution of sex, two sexes and the female germline in relation to the requirement to select for high-quality mitochondrial DNA [R5]. Each of these transitions involves a restructuring of energy flow in relation to genetic information, enabling major leaps in the potential of life.

(iii) **Adaptation and complex traits**. Lane's experimental work on mitochondrial energetics focuses on mitonuclear interactions using *Drosophila* as a model organism. Lane has collaborated across UCL through his founding co-leadership of the UCL Consortium for Mitochondrial Research. Lane authored a theory paper outlining an original hypothesis on the relationship between fertility and longevity based on interactions between mitochondrial and nuclear genes [R6]. Designated the 'Lane hypothesis' by others, it has been formally tested and supported with experimental approaches (Dobler *et al*, *Human Reproduction Update*, 24, 519–534; 2018). This research has implications for adaptation to changing environments and speciation, as well as to personalised medicine, being lauded by the BBSRC as potentially founding a new field of 'pharmacomitogenomics'.

Lane's underpinning research has been supported by grants from the BBSRC, EPSRC, Gates Ventures and Leverhulme Trust, totalling more than GBP5m. His full body of research entails more than 50 peer-reviewed papers since Lane joined UCL in 2009, cited more than 6,000 times (18 papers more than 100 times). The quality of Lane's research is testified by prestigious awards including the BMC Research Award for Genetics, Genomics, Bioinformatics and Evolution (2011) and the Biochemical Society Award (2015).

3. References to the research (indicative maximum of six references)

[R1] Lane N, Martin WF. (2012). 'The origin of membrane bioenergetics'. *Cell* 151, 1406–12.273 citations. Altmetric score: 81 (top 2% all articles of same age). DOI: https://doi.org/10.1016/j.cell.2012.11.050

[R2] Sojo V, Pomiankowski A, Lane N. (2014). 'A bioenergetic basis for membrane divergence in archaea and bacteria'. *PLOS Biology* **12**, e1001926. 86 citations, Altmetric score: 119 (top 1% all articles of same age). DOI: https://doi.org/10.1371/journal.pbio.1002102

[R3] Jordan SF, Rammu H, Zheludev I, Hartley AM, Marechal A, Lane N. (2019). 'Promotion of protocell self-assembly from mixed amphiphiles at the origin of life'. *Nature Ecology and Evolution* **3**, 1705–1714 21 citations. Altmetric score: 281 (top 1% all articles of same age). DOI: https://doi.org/10.1038/s41559-019-1015-y

[R4] Lane N, Martin W. (2010). 'The energetics of genome complexity'. *Nature* **467**, 929–934. 916 citations. Altmetric score 127 (top 1% all articles of same age). DOI: https://doi.org/10.1038/nature09486

[R5] Radzvilavicius A, Hadjivasiliou Z, Pomiankowski A, Lane N. (2016). 'Selection for mitochondrial quality drives evolution of the germline'. *PLOS Biology* **14**, e2000410; 37 citations. Altmetric score: 203 (top 1% all articles of same age). DOI: https://doi.org/10.1371/journal.pbio.2000410

[R6] Lane N. (2011). 'The costs of breathing'. *Science*, **334**, 184–185.. 43 citations. Altmetric score: 28 (top 3% all articles of same age). DOI: https://doi.org/10.1126/science.1214012

4. Details of the impact (indicative maximum 750 words)

Lane's pioneering reconception of the evolution of life in energetic terms has had global reach and influence through his 2015 book *The Vital Question*. This book synthesised his research on energy flows and the origin of life, the evolution of complex cells, and the adaptation of complex traits into an accessible exploration of life, reproduction, ageing, and death. By translating his research into this popularly written form, Lane's research has had four main areas of impact: It has reshaped public perception of evolution; reached millions through extensive media impact; inspired students and the public to engage with and study science; and generated funding and enthusiasm for space missions.

Reshaping media and public perception of evolution

The Vital Question, has sold more than 100,000 copies globally and been translated into 14 languages [S1]. Describing it as "*one of the deepest, most illuminating books about the history of life to have been published in recent years"*, *The Economist* selected it as a book of the year, as did *Nature*, *New Scientist*, *The Times*, *FT*, *Independent*, *Sunday Times*, *Telegraph* and the *Wall Street Journal* [S1]. Reviews highlight how Lane's view of energy has transformed our understanding of life as a cosmic process by challenging the long-established gene-centric mind set. Peter Forbes wrote in the *Guardian* that *"Lane's theories are ingenious, breathtaking in scope and challenging in every sense… intellectually what Lane is proposing, if correct, will be as important as the Copernican revolution."* This challenge to conventional scientific thinking was echoed by Peter Requarth in the *New York Times*, who wrote that *"Dr Lane's broad perspective, which attempts to address the origins of life, sex and death, is seductive and often convincing… Dr Lane's many predictions, however incredible they seem, are testable and could keep scientists busy for years."* Likewise, the geneticist Ravinder Kanda was challenged, writing in the *Times Literary Supplement* that Lane *"approaches the question of the origin of life from a very different perspective: energy…. He certainly made me think about the question from a standpoint that is very different from the one I'm used to as a geneticist*."

The impact of *The Vital Question* was recognised by the Royal Society Michael Faraday Prize, the UK's premier award for excellence in science communication. Lane's prize lecture has been viewed more than 50,000 times on YouTube. The Chair of the Royal Society public engagement committee in 2016 commented that the book *"inspired individuals to embrace science and engineering as a career choice and motivated non-scientists to use evidence-based approaches to address current and key scientific issues affecting humanity"* [S2].

These reviews brought *The Vital Question* to the attention of Bill Gates, who addressed the role of energy in human health on his GatesNotes blog, Facebook and Twitter, with a review and video feature viewed more than 300,000 times on Facebook, with 25,000 shares, 11,000 loves and 1,200 comments [S3]. Gates called attention to Lane's *"attempt to right a scientific wrong by getting people to fully appreciate the role that energy plays in all living things… Lane's focus on energy will be seen as an important contribution to our understanding of where we came from, and where we are going."* Gates was inspired by the practical applications of Lane's work: *"Our foundation's global health team is talking to Nick about potential implications for the fight against malnutrition"* [S3]. Lane has been regularly consulted by the President of Global Health at the Gates Foundation, who states in an email that he met with *"Bill Gates and select scientific leaders"* to give one of *"a small number of updates on key scientific policy issues".* Lane led a discussion on the applications of his research as a springboard *"for a candid conversation about the future of R&D and how emerging scientific innovations can support efforts to tackle the world's greatest health challenges"* [S3].

Generating excitement around, and funding for, space missions

The Vital Question has generated excitement and funding for NASA space missions. A former NASA Associate Administrator for Science wrote that "*I found the book inspirational in presenting a likely pathway to the origins of life on Earth, and on ice-covered ocean worlds such as the moon of Jupiter, Europa, and of Saturn, Enceladus. Working with NASA, the Administration (Office of the President), and Congress, I helped to create an Icy Worlds Research program, and initiated*

the Europa Clipper Mission, led by the NASA Jet Propulsion Laboratory. The Vital Question provided me a sound scientific basis (I'm an astrophysicist) for my support for those planetary science programs" [S4]. The funding committed to the Europa Clipper Mission alone totals USD4bn. This former NASA Associate Administrator and the Director of NASA's Space Telescope program commissioned Lane to feature in a film, 'The Hunt for Planet B', which was designed to generate excitement around the launch of the USD10bn James Webb space telescope in October 2021. With "*unprecedented access to NASA's high-stakes James Webb Space Telescope*", the film is being launched at the influential SXSW Film Festival in March 2021, and will be placed on one of the major streaming TV outlets (Netflix, Amazon, HBO, Discovery, CNN) [S5]. The Producer of 'The Hunt for Planet B' wrote that Lane is "*essential to the film*," as he "*made us understand what life is and what we might find in the universe*" [S5].

Lane helped raise awareness and generate excitement for Breakthrough Initiatives' mission to Saturn's moon, Enceladus. He was interviewed as one of four prominent astrobiologists for a short film designed to raise awareness of the big questions around life in the universe among prominent technology and internet entrepreneurs around the world, with a view to raising funding for potential small-scale space missions to explore some of these questions. The film was shown at five private events between 2017 and 2018, in London, Berlin, Bangalore, Beijing and San Francisco, where it was viewed by leading figures from the tech engineering and investment sectors of those countries [S5]. The Creative Director of Breakthrough Initiatives wrote that Lane "*offered crucial insights into the origin of life on Earth and the chemistry of primaeval deep-sea hydrothermal vents…both his expertise and his infectious excitement about the science played a big part in the excellent response to the film at all the events*" [S5]. The film assisted Breakthrough Initiatives to sign a contract with NASA in 2018 to create the concept for a flyby mission to probe the plumes of Enceladus, the first privately funded deep-space mission.

Conveying the excitement of astrobiology to millions through media impact

In part because Bill Gates thrust the book into the spotlight, *The Vital Question* inspired widespread interest across the media. As a result, Lane has engaged with millions through broadcast media on the question of planetary life. He appeared as an expert on Horizon 'Oceans of the Solar System' (BBC2, 2016; [TEXT REMOVED FOR PUBLICATION])), 'It's Not Rocket Science' (ITV, 2016; [TEXT REMOVED FOR PUBLICATION]) and 'Secrets of the Solar System' (CuriosityStream/ Yesterday, 2020). Lane has advised on the making of other programmes, including 'One Strange Rock' (National Geographic, 2018, with over 100 million viewers worldwide [S6] and 'Forces of Nature' (BBC with Brian Cox, 2016; 2 million viewers worldwide). He was scientific consultant and featured as an on-screen expert on the US/international version of episode two, 'Mars and Earth' for Brian Cox's 'The Planets', made by the BBC and screened by NOVA in the US ([TEXT REMOVED FOR PUBLICATION]). On national radio, Lane has been interviewed on BBC Radio 4's 'The Life Scientific' (2016), 'In Our Time' (2018, 2015, each listened to approximately 3 million times), 'Infinite Monkey Cage' (2016), 'Inside Science' (2018, 2017), 'Today Programme' (2015) and 'Start the Week' (2015). A book celebrating 20 years of 'In Our Time' shows how much Lane's ideas have engaged the public. The book features 50 programmes (of which 10 are on science) from over 900 recorded. The Producer of 'In Our Time' wrote: *"[We] have been looking at the programmes that listeners say they've enjoyed the most and, while it's a very long list, we've chosen 'Photosynthesis'* [featuring Lane] *as one of those for the Science section. It has proved a very popular edition since it was broadcast"* [S6]. Online platforms featuring Lane's work include Aeon, Nautilus, Buzzfeed and Radiolab (with 12 million listeners to the podcast and radio show) [S6]. The inspirational impact of Lane's engagement is captured in an email from Scientific Director of the University of California Berkley Innovative Genomics Institute, who wrote: *"I loved the recent episode of Radiolab… I have assigned the Radiolab episode featuring yourself to my students this semester in Genetics and Society, and will do so next semester in Biology for Voters"* [S6].

Inspiring students and the public to engage with and study science

The Vital Question is now widely recommended on reading lists at universities including Oxford and Cambridge (e.g. 'So You Want to Go to Oxbridge? Tell me about a Banana') and in online student forums e.g. the Student Room. Since 2015 Lane has given more than 20 talks in schools.

Lane's writing has inspired pupils who would not have considered STEM to take a biology degree; UCL admissions records show that 50% of students cite Lane's book on their UCAS form as an inspiration for applying to study biology. A teacher at Colchester Royal Grammar wrote: *"I wanted to let you know the lasting impact your lecture had for my students. Many are now in year 13 and have been busily writing their personal statements for UCAS this term. Quite a few of them mention your talk, and the additional reading that this then led them to undertake. One student in particular wrote extensively about his learning from your books and is today being interviewed at Oxford for Biological Sciences!"* [S7]. Lane spoke at two Molecular Frontiers events for schools at the Swedish Royal Academy of Sciences (in 2019 and 2017), and featured in an inspirational short video for students [S8]. He has given over 30 public talks at science and literary festivals since 2015. Reaching more than 15,000 people directly, many of these talks were recorded and are available on YouTube, where they have had more than 300,000 views [S1]. The reach of Lane's ideas is illustrated by a transmission on the South American YouTube channel Migala, viewed live by over 30,000 people, despite being in English. The host Pepe wrote that the transmission was so inspirational that *"people in the chat started to translate the conversation for those who couldn't understand. Also, a couple volunteers started working on the Spanish subtitles already, so a lot more people are going to listen to it"* [S9].

Eric Idle, of Monty Python fame, attended one of Lane's public lectures in 2016 and was inspired to write a musical on the subject of death—one of the key topics explored in *The Vital Question*. He emailed to say: *"As I have only a bare pass in O level Physics with Chemistry and that's my only science it is a compliment to you to say how much fun I find [your writing]… I think laymen are intrigued by things that really exist in the Universe. We can't help it. You do a great job of explaining. I've been working on a new musical which deals with the subject of death and I would like to fact check it. It's for 'Death the Musical'… My play seeks to cheer people up in the face of their own mortality. Bright Side and all that..."* [S10].

5. Sources to corroborate the impact

[S1]: letter from Profile books/United Agents to confirm these numbers.
[S2]: Email from Prof Russell Foster, Chair of Royal society public engagement committee in 2016; lecture: https://royalsociety.org/science-events-and-lectures/2017/02/faraday-prize-lecture/
[S3]: https://www.gatesnotes.com/Books/The-Vital-Question; https://twitter.com/BillGates/status/729796241064927233; https://www.facebook.com/BillGates/videos/the-vital-question-with-nick-lane/10153567282026961/; Email from Trevor Mundel, President, Global Health, Gates Foundation.
[S4]: Email from former NASA Associate Administrator for Science John Grunsfeld.
[S5]: Emails from Nathaniel Kahn and Bonnie Hlinomaz, (Director and Producer of *The Hunt for Planet B)* and Adam Rosenthal (Creative Director of Breakthrough Prize).
[S6]: Testimonials confirming media impact of *The Vital Question*:

- Email from Sophie Mautner, Nutopia, confirming National Geographic and Netflix viewing figures.
- Email from Simon Tillotson, Producer of 'In our Time'.
- Email from Robert Krulwich, co-host of 'Radiolab' and Fyodor Urnov, listener and teacher.

[S7]: Email from Ayala Daisly, Colchester Royal Grammar School.
[S8]: Prof Lane featured in inspirational film about how Molecular Frontiers symposia engage with schools: https://www.youtube.com/watch?v=2oluTiaxB5s&t=5s.
[S9]: Email from Jose Luis Hernandez, 'Pepe', host of *Migala* YouTube channel.
[S10]: Email from Eric Idle of Monty Python about 'Death the Musical'.