Institution: University of Edinburgh		
Unit of Assessment: UoA 9 - Physics		
Title of case study: Employing polymer physics to improve gluten-free bread structure		
Period when the underpinning research was undertaken: 2007–2016		
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:**
Prof. Wilson Poon	Professor	1990 – present
Prof. Alexander Morozov	Professor	2007 – present
Dr Keith Bromley	PDRA	2012 – 2019
Period when the claimed impact occurred: February 2016–December 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Attribution: University of Edinburgh (UoE) researchers pioneered an approach to explore the rheology of caramel, a complex, multi-component food inhabiting a multi-dimensional parameter space, interpreting the data using their expertise in colloidal aggregation and polymer dynamics. A similar approach was then used to understand why the rheology of gluten-free dough often led to instability in baking, and how this could be alleviated.

Impact: Working with a Scottish company, *Genius Gluten Free Ltd.*, UoE researchers quantified how different ingredients affected dough stability [text removed for publication].

Beneficiaries: As well as helping the company remain one of the top gluten-free providers in the UK and grow its world market, the collaboration has resulted in products of more consistent quality for *Genius*' gluten-free customers.

Significance and reach: [text removed for publication] The company is a pioneer of the fresh gluten-free bread market, and the partnership with UoE has helped them remain a top brand within an increasingly competitive market.

2. Underpinning research

Soft matter physics studies colloids, polymers, and surfactants. Most food ingredients are soft matter, as are most foods in the form in which they are consumed. Soft matter physicists have therefore long been associated with food research. Two strands of UoE's soft matter physics research underpin our work with *Genius Gluten Free Ltd*.

First, many soft matter systems are viscoelastic: their flow and deformation show characteristics of both viscous liquids and elastic solids. Prof Morozov is a world-leading expert in the flow instabilities of viscoelastic materials. A famous example is the melt-fracture phenomenon observed in the extrusion of concentrated polymer solutions or melts. In this process, the liquid is pressed through a thin capillary to produce a regular jet of material. At low extrusion speeds the jet remains straight and homogeneous, while at larger speeds the flow starts undulating, becomes chaotic and eventually breaks up. These instabilities are one of the main production-limiting factors and have been plaguing industry for years. Morozov was the first to propose [***R1***] that these phenomena are linked to a sub-critical instability leading directly to so-called 'purely elastic turbulence' – a chaotic flow state observed in viscoelastic materials at low Reynolds numbers. He teamed up with the experimental group of Professor Arratia (UPenn, USA) to convincingly establish this connection [***R2***]. This expertise helped pinpoint a key flow instability in gluten-free dough.

Secondly, soft matter physicists studying food typically investigate single ingredients, e.g., how one milk protein forms gels under heating. Sometimes, binary mixtures of ingredients are also tackled. However, real foods with 3 or more components are usually considered too complicated for physicists. In a key paper [***R3***], Prof Poon demonstrates how the physics approach can nevertheless be used to reveal surprising simplicity in a complex food system. Central to this approach was the idea of 'subtractive formulation' – stripping the caramel to just the essential ingredients, *but no simpler*. This still left a four-component composition space (water, sugars, proteins, fats) to be navigated to 'tune' the properties of the product.

Poon measured the response of a range of caramels within this composition space to mechanical oscillation at various frequencies. The real and imaginary parts of the response function were found to scale into a single pair of universal curves spanning 13 orders of magnitude in frequency. Importantly, these curves were identical to those of filled polymers, a well-known class of soft matter that includes rubber strengthened by nanoparticles. Their conclusion is that changing any of the many parameters in making caramel in effect only 'tunes' two underlying parameters controlling the caramel's flow properties: a fundamental relaxation time and a cross-linking density of denatured proteins. Poon and Weir also established regions within their four-dimensional 'ingredient space' in which caramel preparation failed, linking the failure modes to physical phenomena such as percolation. Their results mean that manufacturers can optimise new or existing recipes rationally rather than through trial and error. The approach exemplified in this study of caramel rheology [***R3***] was subsequently adapted by UoE researchers to study the rheology of gluten-free dough and isolate the effect of different ingredients [text removed for publication].

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

[***R1***] W. Becherer, W. van Saarloos and **A. N. Morozov**, *Stress singularities and the formation of birefringent strands in stagnation flows of dilute polymer solutions*, J. Non-Newtonian Fluid Mech. 157, 126 (2009) DOI: https://doi.org/10.1016/j.jnnfm.2008.09.001 *[12 citations, WoK]*

[***R2***] L. Pan, **A. Morozov**, C. Wagner and P. E. Arratia, *A Nonlinear Elastic Instability in Channel Flows at Low Reynolds Numbers*, Phys. Rev. Lett. **110**, 174502 (2013) DOI: https://doi.org/10.1103/PhysRevLett.110.174502 *[91 citations, WoK]*

[***R3***] Simon Weir, **Keith M. Bromley**, Alex Lips and **Wilson C. K. Poon**, *Simplicity in complexity – towards a soft matter physics of caramel*, *Soft Matter* **12** 2757-2765 (2016) DOI: https://doi.org/10.1039/C5SM01797A *[5 citations, WoK]*

4. Details of the impact

Moving from caramel to instabilities in GF bread

Gluten intolerance is widespread, with coeliac disease affecting 1% of the European population [***I1***]. Historically, gluten-free (GF) bread was hard, dense and dry, and eaten only out of necessity. Lucinda Bruce-Gardyne, FRSE, founded *Genius* in 2008 after creating the first fresh white and brown GF sliced loaves equalling mainstream wheat bread in quality and cost (Figure 1). The company now sells over 25 products worldwide, developed and manufactured mostly in Bathgate, Scotland, with an annual turnover of GBP34,000,000 [***I2***].

Figure 1: The Genius Food brand and their fresh, sliced, gluten-free loaf.

Genius learned about the above-mentioned UoE expertise when their Research Manager met UoE's Dr Keith Bromley at a food-science conference. Subsequent discussions with the company suggested to both parties that the approach used in [***R3***] to study complex foods could be adapted to solve a long-standing problem: the instability of GF dough. Excluding gluten from dough dramatically increases its sensitivity to small variations in recipe or processing conditions: a 5g difference to one ingredient in a 2kg GF bread mix makes the difference between a high-quality loaf and a holey, crumbling one (Figure 2). Such sensitivity drives up costs for the company and lowers product consistency for the consumer.

The overwhelming majority of the literature on wheat dough emphasizes gluten's elastic properties, and the GF literature typically discusses how to replace the elasticity lost due to the absence of gluten. Drawing on previous experience with polymer flow instabilities in

confined spaces [***R1, R2***], the UoE team rapidly homed in on a different issue. [text removed for publication].

Guided by previous experience in developing a model caramel using the 'subtractive formulation' approach, the team developed a model GF dough, which allowed them to test rapidly the effect of various ingredients [text removed for publication].

[text removed for publication]

Mentorship for University of Edinburgh entrepreneurs

As a result of the UoE-*Genius* collaboration, a productive working relationship was established between the University and the company's founder, Lucinda Bruce-Gardyne. This led to a successful application to the Royal Society to appoint her as the Entrepreneur in Residence within the School of Physics and Astronomy (2018–20). Bruce-Gardyne's work has created an outward-facing, entrepreneurial culture amongst the School's early-career researchers (ECRs), and has expanded their ambition beyond academic work at a crucial stage of their career. Bruce-Gardyne has organised 32 master classes [***I5***] (average attendance of 25, mostly ECRs) in which a diverse range of speakers, many of whom are physicists-turned-entrepreneurs, have imparted their experience of moving from research to business. Bruce-Gardyne has also provided mentoring to ECRs who have successfully started three companies [***I6***]: Dyneval, a company using specialised microscopy to characterise particle dynamics, initially focussing on animal sperm motility for fertility applications [***I7***]; QuestPair, which specialises in matching academic experts with companies [***I8***]; and InVed, a company using patented technology to create environmentally-friendly personal care products [***I9***].

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

[***I1***] Epidemiology of celiac disease: Singh, Prashant et al., Global Prevalence of Celiac Disease: Systematic Review and Meta-analysis, *Clinical Gastroenterology and Hepatology*, **16** 823 -836.e2 DOI: https://dx.doi.org/10.1016/j.cgh.2017.06.037

[***I2***] A PDF of the Company House records (year ended 31st December 2019) can be downloaded here: https://find-and-update.company-information.service.gov.uk/company/SC344777/filing-history

Direct link to PDF: https://find-and-update.company-information.service.gov.uk/company/SC344777/filing-history/MzI4Njg1ODc4NmFkaXF6a2N4/document?format=pdf&download=0

[***I3***] Support letter from the CEO of Genius Gluten Free Ltd

[***I4***] Product details on Genius website: https://geniusglutenfree.com/en_gb/products

[***I5***] Masterclass events archive: https://www.ph.ed.ac.uk/industry/entrepreneurial-hub/masterclasses-and-workshops/entrepreneurship-events/archive

[***I6***] Corroborating contact: Founder of Genius Foods Ltd. Can verify masterclasses and mentorship

[***I7***] Corroborating contact: CEO of Dyneval (https://www.dyneval.com/). Can verify mentorship.

[***I8***] Corroborating contact: Co-founder and CEO of QuestPair (https://questpair.com/). Can verify mentorship.

[***I9***] Corroborating contact: Founder of InVed. Can verify mentorship.