Final report

EPSRC review of doctoral education

A review of the literature

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Preface

This report presents the findings from a literature review on doctoral education in engineering and physical sciences conducted as part of a review of doctoral education currently being conducted by the Engineering and Physical Sciences Research Council (EPSRC). It describes the background, methodology used and the findings of the study.

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Executive summary

Doctoral education is a critical aspect in building the talent base that will deliver the UK Research and Development (R&D) Roadmap,[1] as the skills acquired through doctoral training can be utilised in multiple sectors of the economy. STEM (science, technology, engineering and mathematics) doctoral students are considered particularly valuable to "the new economy, which trades principally in knowledge" (Barnacle 2005). It is thought that STEM doctoral graduates enable the flow of knowledge across organisations and businesses and can apply their creative problem-solving skills to the development of innovation.

The Engineering and Physical Sciences Research Council (EPSRC) is the main public funding body for engineering and physical sciences in the UK, funding approximately one third of all engineering and physical sciences doctoral students in the UK. The EPSRC has been innovative in its development of doctoral training, adapting its delivery models throughout the years to best meet the needs of doctoral students, as well as the changing research landscape. The EPSRC is undertaking a review of their investment in doctoral education.

To provide evidence for EPSRC's review, RAND Europe conducted a literature review of the currently available evidence on the value, skills and career outcomes of doctoral education in engineering and physical sciences, as well as novel approaches to doctoral education. The search resulted in 4,455 studies of which 114 were included in the review. The literature was limited to publications in English between 2011-2021, and included both academic and grey literature (e.g. policy reports). Analysis of the literature was also informed by scoping interviews with five experts in higher education policy.

RQ1: What is the value of an engineering and physical sciences doctoral education?

The evidence from the reviewed literature indicates that doctoral education provides value in several ways and is beneficial to the individual, potential employers, and society more broadly (Box ES.1). The evidence available from the UK was limited, and therefore where relevant we have drawn insights from literature based elsewhere including Spain, Australia, and the United States (US). Although there are likely to be differences between doctoral education across different countries, we believe that many of the results on the value of

[1] HM Government (2020) UK Research and Development Roadmap. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/896799/UK_Research_and_Development_Roadmap.pdf

doctoral education are generalisable across different countries, and findings from UK-based studies were commonly supported by European and US sources.

Box ES.1 Key findings on the value of an engineering and physical sciences doctoral education

Doctoral students in the engineering and physical sciences provide value through the research they generate

- Doctoral education in engineering and physical sciences allows students to develop new knowledge that is particularly valuable to society, since it has the ability to tackle societal challenges across the social, political, cultural, technical, environmental and health spheres.
- Doctoral graduates serve as important channels for knowledge transfer between universities and private firms.

Doctoral education in the engineering and physical sciences provides value to the individual by enabling the development of technical and transferable skills

- Doctoral education enables students to become part of the wider knowledge economy.
- Doctoral education may support students in developing their wider professional networks.
- There is evidence that doctoral graduates within STEM may have improved career outcomes including better prospects, higher salaries, more interesting work, and ultimately improved career trajectories.

Employees carrying doctorates in the engineering and physical sciences may be valuable to employers

- There was mixed evidence on the potential added value to employers when hiring doctoral graduates compared to graduates with an undergraduate degree.
- There was evidence of growing realisation that the technical skills developed by STEM doctoral graduates are transferrable to non-academic careers and may bring significant value to non-academic employers.
- However, the value of hiring doctoral graduates is not always clear to non-academic employers.

RQ2: What are the eventual careers of engineering and physical sciences doctoral graduates?

The evidence demonstrates that doctoral graduates within engineering and physical sciences move into a range of careers, although the majority will pursue a career in academia or industry (Box ES.2). The majority of studies reviewed were based in the US, and therefore the applicability of the findings to a UK context should be taken with caution. However, several of the studies included in this section were from European countries including Finland, Germany, Portugal, Austria, Sweden, and Spain and therefore the results should offer some insights into doctoral education more broadly.

Box ES.2 Key findings on the eventual careers of engineering and physical sciences doctoral graduates

The evidence suggests that doctoral students in the engineering and physical sciences are likely to embark on both academic and non-academic positions, with differences between disciplines

- For doctoral students in engineering, there was consistent evidence that most students find employment in industry or business, although the majority of these studies were based in the US. A 2015 survey by the National Science Foundation (NSF) found that 14.4% of engineering doctoral students in the US had employment within academia while 72.1% found employment in industry or business.
- For doctoral students in physics, there was some evidence that students are likely to embark on both academic and non-academic positions. In the US, postdoctoral positions were the most likely form of employment immediately following a physics doctorate and remain likely careers up to three years after completing a doctorate. Where physics doctoral graduates in the US did move on to permanent positions in the private sector, these were commonly in the fields of computer software, engineering and data science.

Studies have highlighted a changing labour market for doctoral graduates, although these are based in the US

- Evidence from the US shows that although the number of science and engineering doctoral graduates has increased in the last 30 years, available tenure-track positions have declined.
- A survey of the career preferences of science doctoral students in the US found that although academic careers (research and teaching) and careers within R&D (industry and government) were rated as the most attractive, other careers mentioned by students included science communication, science policy, non-university teaching, consultancy and working for non-profit organisations.

The evidence suggests that research interests may play a role in the career outcomes of doctoral graduates

- Connections and collaboration with industry during doctoral studies may contribute to students' interests in careers outside of academia.
- Students with greater interest in basic research and peer recognition were more likely to pursue a career in academia and those with an interest in applied research and an interest in gaining professional experience were more likely to pursue careers outside of academia.
- Doctoral supervisors may also play a role in students' preferred career path.

The academic research environment may deter doctoral students from pursuing a career in academia

- A US survey showed that the attractiveness of an academic career declined for both physics and chemistry doctoral students over the course of their doctoral education.
- Doctoral students may seek employment outside of academia due to the limited number of permanent positions within academia, changing research interests, imbalance of workload and salary, better paid positions in industry, pressures of working in an academic environment (e.g. grant writing), and the politics of academia.

There was mixed evidence on the role that gender may play in the eventual careers of doctoral graduates

- A number of studies, each looking at different engineering and physical sciences disciplines, found that female doctoral students were less likely to stay in academia than their male counterparts, whereas another study, looking 5-6 years post-graduation, found that female engineering doctoral students were more likely to stay within the academic environment and that male doctoral students were more likely to go into industry.

RQ3: What are the common skills requirements for doctoral graduates across all engineering and physical science sectors?

The diverse range of potential careers creates a variety of skills requirements for graduate students. Doctoral graduates go on to pursue careers in multiple sectors of the economy, including the charity/not-profit and public sector (Box ES.3). However, our review mainly found evidence on the skills requirements for engineering and physical sciences doctoral students in academia or industry, with no reference to the skills required in other sectors of the economy. From the studies reviewed there was limited number of UK-based studies, and therefore where relevant we have drawn insights from literature based elsewhere including studies from several European countries, the US, New Zealand, and Canada. The diversity of countries that were involved builds an informative picture of the global skills requirements for doctoral education and consistent trends were highlighted in the literature including the increasing focus on transferable skills, and increased diversity of career paths for doctoral graduates.

Box ES.3 Key findings on the skills requirements of engineering and physical sciences doctoral graduates

Doctoral education provides individuals with both 'hard' and 'soft' skills

- Hard skills typically refer to skills that are acquired through education or training and are generally measurable and easy to quantify. On the other hand, 'soft skills' refer to interpersonal and emotional skills such as teamwork.
- Hard skills developed during a doctorate include scientific writing, creating and delivering presentations, investigating systems and teaching, as well as technical skills.
- Soft skills developed during a doctorate involve skills such ability to manage projects, ability to learn quickly, and creative thinking.

Specialisation in certain skillsets may not adequately prepare students for varying and multidisciplinary environment

- Specialisation in a narrow research field doctoral students undertake when completing their studies may prevent graduates from developing soft skills and adequately preparing for multidisciplinary research environments.
- Specialisation in discipline-specific skills may be counterproductive in a private sector setting.
- Doctoral graduates should improve their business management skills, like project management or balancing a budget in order to succeed in industry, which can be acquired through entrepreneurship training, for example, during doctoral education.

The demand for skills is changing globally, creating a need for new types of doctoral training

- Whereas the traditional model of doctoral education might consider a doctoral student as a type of 'academic apprentice', focussing on developing specialised skillset and becoming an expert on a specific topic or field, the UK's research system now follows a 'knowledge economy' model where education in STEM, knowledge, and innovation are prerequisites for economic growth.
- As more doctoral students look for roles outside of academia, they must apply the skills developed in their doctoral education in this new environment.

The skills required from doctoral graduates vary by sector, although there are common skills between them

- There are common skills valued by the academic sector and industry from doctoral graduates, such as problem solving, teaching, written communication, research methods, critical thinking, collaboration and teamwork, and project management.
- Skills specific to the academic sector include researcher autonomy, technical knowledge, writing grant proposals and mentorship.
- Skills specific to industry include time management, leadership, business management, financial skills, strategy, and risk management.

RQ4: What is the current community's opinion of the future of doctoral education, including any novel approaches?

Given the importance of transferable skills described in the literature across sectors it is perhaps unsurprising that community opinion on the future of doctoral education suggested a shift towards an increasing transferable skills-based approach to support doctoral students as they embark on their careers. Our review highlighted several areas of potential interest for the future of doctoral education and examples of novel approaches (Box ES.4). However, there is limited evidence of the impact of these approaches. Where relevant we have drawn insights from literature based elsewhere including the US, Italy, Finland, Norway, Germany and Spain, as there was a limited number of UK-based studies.

Box ES.4 Key findings on the future of doctoral education in engineering and physical sciences

There is a shift towards a transferable skills-based approach

- Greater development of transferable skills would support doctoral students for future careers.
- Professional doctorates, cooperative doctorates, and industry placements may offer routes to doctoral students gaining skills other than research and subject-specific skills.
- Alternative models for doctoral outputs may be useful to consider.

There is a need for tailored programmes to support student development during their doctoral education, including:

- Training to support graduates entering academia.
- Tailored programmes to better prepare students for a career outside of academia.
- Initiatives to support underrepresented groups.

Greater support for doctoral students should be available to improve their doctoral experience

- Doctoral students need better support with careers advice during their doctorate.
- Greater links between private companies and universities are beneficial to graduates that seek to transition into industry.
- Mentorship and group supervision may provide useful support to doctoral students during their studies.

Gaps in the existing evidence base

Findings from the literature review offer insight into some of the research questions presented in this study. However, we identified areas where the evidence was lacking and future research could prove beneficial to better understand the UK landscape for doctoral education in engineering and physical sciences.

There is a lack of UK-based studies across the research questions. Most of the literature focused on contexts other than the UK. In particular, a vast number of studies were US-based, a system for doctoral education and career pathways that differs significantly from that in the UK. Therefore, the applicability of our findings to the UK context is limited. However, our literature review focused exclusively on the existing literature on engineering and physical sciences, and it is likely that most studies available in the UK focus on the outcomes of doctoral education more widely rather than taking a discipline-specific approach.

There is limited evidence on the skills requirements of certain sectors such as the charity or not-for-profit sector. We found multiple studies that describe the skills requirements from engineering and physical sciences doctoral students in both academia and industry. However, less evidence was available on the skills requirements for other sectors of the economy including the charity/not-profit sector, the public sector or policymaking.

There is a lack of comparative or longitudinal studies to assess the outcomes of doctoral education in engineering and physical sciences. To fully assess the impact of doctoral education, there is a need for comparative studies that take into account outcomes of undergraduates, masters or doctorates. In addition, longitudinal studies would enable us to better assess how doctoral graduates progress in their careers and how doctoral education contributed to this progression.

Studies discussed different approaches to doctoral education but did not offer an analysis of the impact of these approaches on doctoral outcomes. Our review included evidence on novel approaches to doctoral education in engineering and physical sciences, as well as identified areas for improvement in the current system. However, the impact of the different approaches proposed was not assessed and therefore the validity of these cannot be confirmed. Similarly, despite the changing research landscape in academia, no studies discussed how doctoral education has adapted in light of these changes (e.g. Open Science, researcher mobility, etc.).

Strengths and limitations of the study

Our study provides a broad overview of the literature on the value of doctoral education in engineering and physical sciences. An REA provides a systematic and robust approach to reviewing the evidence. Our broad global scope and the use of three databases (Web of Science, ERIC and Scopus) enabled us to capture information across the relevant disciplines and countries of interest. There were however several limitations to this study. Firstly, an REA is not a systematic review of the literature, and it is possible that relevant literature was not included as the search terms were more restrictive. Secondly, the study was limited to publications in English and therefore relevant articles would have been missed if published in another language.

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Abbreviations

ACADEME	Advancing Career in Academics with Diversity and Mentorship in Engineering
CIFRE	Conventions Industrielles de Formation par la Recherche
EDI	Equality, diversity and inclusion
EngD	Engineering Doctorate
EPSRC	Engineering and Physical Sciences Research Council
ERIC	Education Resources Information Center
iFEAT	Illinois Female Engineers in Academic Training
NSF	National Science Foundation
OPTIONS Program	Opportunities for PhDs: Transitions, Industry Options, Networking and Skills
PhD	Doctor of Philosophy
R&D	Research and development
REA	Rapid Evidence Assessment
RRI	Responsible Research and Innovation
STEM	Science, Technology, Engineering and Mathematics
UK	United Kingdom
US	United States

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1. Engineering and physical sciences doctoral education in the UK

The UK Government has recognised the importance of research and innovation to the UK economy through its aim to increase investment in research and development (R&D) to 2.4% of GDP by 2027, which will be implemented through the UK Research and Development Roadmap.[2] Within this Roadmap there is a strong commitment to support people through attracting, training and retaining diverse talent within the R&D workforce across all employment sectors. This is highlighted by the People and Culture Strategy which sets out the governments ambition to build a research workforce that ensures the UK provides a positive and inclusive culture.[3] Doctoral education is a critical aspect in building this talent base, as the skills acquired through doctoral training can be utilised in multiple sectors of the economy.

Traditionally, doctoral education followed an 'apprentice model', in which a doctoral researcher would work with or alongside a supervisor to address a research question. Using this approach, doctoral education aimed to train the next generation of academics. However, in the last decade doctoral education has been transformed into a much more comprehensive programme of training involving a supervisory team and staff from across the institution and beyond (Spronken-Smith 2018, Willey 2019).

The change in delivery of doctoral education has been led by a change in the perception of its purpose, the advent of a global knowledge economy and the important role that doctoral graduates play in the production of knowledge and innovation. STEM (science, technology, engineering and mathematics) doctoral students are considered particularly valuable to "the new economy, which trades principally in knowledge" (Barnacle 2005). It is thought that STEM doctoral graduates enable the flow of knowledge across organisations and businesses and can apply their creative problem-solving skills to the development of innovation. Sir Gareth Roberts' SET for Success report (2002)[4] highlighted that doctoral education was not preparing doctoral graduates effectively for careers within academia or other employment sectors. The subsequent ring-fenced institutional funding (2003 – 2011)

[2] HM Government (2020) UK Research and Development Roadmap. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/896799/UK_Research_and_Development_Roadmap.pdf

[3] HM Government (2021) Research and development (R&D) people and culture strategy. https://www.gov.uk/government/publications/research-and-development-rd-people-and-culture-strategy

[4] Roberts, Gareth Gwyn, HM Treasury, corp creator. SET for success: the supply of people with science, technology, engineering and mathematics skills: the report of Sir Gareth Roberts' review.

led to a step change in institutional provision for doctoral education through the introduction of comprehensive researcher development programmes.[5] Over the same period we have seen the growth of Graduate Schools and Doctoral Colleges, and the introduction of Codes of Practice for doctoral education,[6] supervisor guidelines and statements on the roles and responsibilities of doctoral researchers bringing much more consistency into the processes and practices within doctoral degrees.

A Statement of Expectations for Postgraduate Training was issued by Research Councils UK in 2010, and adopted by other major funders, such as Wellcome, British Heart Foundation and Cancer Research UK,[7] which outlined the expectations on institutions in recruiting candidates based on merit and providing an excellent research environment, as well as expectations on doctoral researchers and collaborators or partner organisations. Similar needs to broaden doctoral education were identified across Europe. The inclusion of doctoral education as a third cycle of study in the framework of the Bologna Process[8] sought to increase the number of doctoral graduates that were better prepared for non-academic labour markets with the aim of developing Europe into a competitive and dynamic knowledge-based economy (Bao, Kehm et al. 2018).

The research landscape is also currently undergoing significant changes. There is increased focus on research integrity and openness in research through, for example, Responsible Research and Innovation (RRI).[9] The research environment and culture are under increased scrutiny, particularly with respect to wellbeing and mental health, bullying and harassment and equality, diversity and inclusion (EDI). A key element of RRI is the greater inclusion of stakeholders, including individuals from industry, interest groups, and society more broadly, throughout the research process including from the inception to the communication of outputs and realisation of impact.[10] In addition, the UK R&D Roadmap and the need for increased investment in R&D by industry to drive R&D activity, has put increased focus on the intersectoral mobility of researchers as well as the capacity of businesses to employ researchers.

In light of these changes, the Engineering and Physical Sciences Research Council (EPSRC) – the main UK public funding body for engineering and physical sciences – is currently undertaking a review of their investment in doctoral education that will cover five areas of doctoral education:[11]

- The value of doctoral education to individuals, employers and society.

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[5] As of 16th June 2021: https://www.vitae.ac.uk/impact-and-evaluation/examples-of-institutional-practice/institutional-case-studies-researcher-development-post-roberts-funding

[6] See for example: https://www.cambridgestudents.cam.ac.uk/grad-code-of-practice/code-practice-research-students

[7] As of 16th June 2021: https://mrc.ukri.org/documents/pdf/statement-of-expectation-studentships/

[8] As of 16th June 2021: http://ehea.info/cid102847/third-cycle-doctoral-education-2009.html

[9] See for example: https://epsrc.ukri.org/research/ourportfolio/themes/healthcaretechnologies/strategy/toolkit/home/integrity/ri/

[10] https://ec.europa.eu/programmes/horizon2020/en/h2020-section/responsible-research-innovation

[11] As of 16th June 2021: https://epsrc.ukri.org/skills/students/review-of-epsrc-support-for-doctoral-education/

- The skills and experiences that should be provided by a doctorate.
- Tools to enable a more diverse student population, including increased mobility between academia and industry.
- The ways in which doctoral education is provided including different qualifications, ways of providing the doctoral experience and how support is provided.
- Ways of identifying, developing and responding to strategic priorities and how the landscape can respond to changing directions and needs.

The first part of the review involves gathering evidence from the community in its widest sense to inform the development of recommendations on the future of EPSRC's support for doctoral education. This report presents the findings from a literature review that will contribute to this evidence base. Additional evidence will be collected through focus groups (carried out by Vitae as part of this study to complement the findings from the literature review) and through workshops (outside of the scope of this study) with different stakeholder groups, including academics, learned societies, businesses; focus groups with doctoral students; analysis of existing datasets; and strategic conversations with stakeholders. Together, these data will enable the EPSRC to develop recommendations for the future of their doctoral education provision.

2. What is the value of an engineering and physical sciences doctoral education?

In this chapter, we explore the evidence from the literature identified on the value of an engineering and physical sciences doctoral education including:

- the value of doctorates through the research they generate;
- the value of the experience and qualification to the individual doing the doctorate; and
- the value of hiring someone with a doctorate in the engineering and physical sciences.

Studies included in this section were selected based on their overall applicability and relevance to the question of value relating to doctoral education in the engineering and physical sciences. From the studies reviewed there were a small number of UK-based studies, and therefore where relevant we have drawn insights from literature based elsewhere including Spain, Australia, and the US. Although there are likely to be differences between doctoral education across different countries, we believe that many of the results on the value of doctoral education are generalisable across different countries, and findings in the UK-based studies were commonly supported by the European and US sources.

2.1. Key findings and summary of the evidence on the value of engineering and physical sciences doctoral education

Key finding	Number of sources	Number of sources based in UK	Strength of evidence	Applicability of findings to UK context
Doctorates in the engineering and physical sciences provide value through the research they generate	7	3	**Moderate –** Three studies were based on literature reviews/narrative reviews of evidence and four studies were empirical studies. These empirical studies used surveys and in-depth interviews data collection methodologies.	**Moderate/High** – Three studies focused on the UK, one was relevant to the wider European context (specifically Spain), and the rest were from the USA or Australia. The consensus of ideas between the UK and non-UK studies was fairly high, all highlighting the value of doctoral research.
Doctoral education in the engineering and physical sciences provide value to the individual by enabling the development of technical and transferable skills	5	3	**Low/Moderate –** Three studies were based on literature reviews/narrative reviews of the evidence, and two were empirical studies. These two studies used online surveys and in-depth interviews to collect data.	**High** – Three studies were directly based in the UK, while the other two were relevant to a European context (Slovenia and an EU regional perspective). The cross over between the UK and non-UK studies was fairly high, all highlighting the development of technical and transferable skills.
Employees carrying doctorates in the engineering and physical sciences may be valuable to employers	7	2	**Moderate** – Five studies cited were empirical studies, one used secondary data and the other three used surveys to collect primary data. The other two were reviews of the literature, one specifically structured as an argumentative piece.	**Moderate** – Two studies were from the UK and three had a European perspective (Finland, Spain, Austria). Two studies focused on Australia and one focused on the USA. There was cross over between the UK and non-UK studies, as both highlighted how PhDs are now more likely to enter into non-academic roles after their degrees, but non-UK studies were more likely to expand on the transferable skills PhDs gain which relate to industries.

2.2. Doctorates in the engineering and physical sciences provide value through the research they generate

Overall, the evidence indicates that doctoral education in the engineering and physical sciences provides value through the research that individuals generate. One study, based in the UK, highlighted the vital role of STEM doctoral students in the generation of new knowledge, defining doctoral students as ‘knowledge workers’ who combine interdisciplinary knowledge, research and transferable skills, reflection, and occupational experience (Hancock and Walsh 2016). This new knowledge has been suggested as particularly valuable to society, since it has the ability to tackle societal challenges across the social, political, cultural, technical, environmental and health spheres (Arnaldo Valdés, Crespo Moreno et al. 2012, Hancock 2019, Parker 2019). A US based study discussed the idea that doctoral students may eventually become leaders in their respective fields and will ultimately address the challenges facing society today (Parker 2019). As well as the creation of new knowledge, doctoral students may facilitate its spread, serving as important channels for knowledge transfer between universities and private firms (Schwabe 2011, Garcia-Quevedo, Mas-Verdu et al. 2012, Hancock 2016, Ortega 2018).

2.3. Doctoral education in the engineering and physical sciences provides value to the individual by enabling the development of technical and transferable skills

Overall, the evidence indicates that doctoral education in the engineering and physical sciences provides value to the individual researcher through enabling them to develop both technical and transferable skills.

As highlighted in the previous section, doctoral education enables students to acquire scientific knowledge with value to society. This knowledge also has value to the individual, enabling them to become part of the wider knowledge economy. One study – based on focus group, survey, and interview data from doctoral students in the UK – highlighted the important role that doctoral education plays in enabling graduates to become part of the knowledge economy (Hancock 2019). This has been highlighted as important both in the UK, but also internationally (Hancock and Walsh 2016, Bao, Kehm et al. 2018, Hancock 2019). As well as gaining scientific and technical knowledge throughout their studies, the literature suggests that doctoral students develop transferable skills, and professional competencies, that may prepare them for their future careers (Hribar 2015, Hancock 2016, Wyckoff 2016, Hancock 2019).[12] In addition, doctoral education may support students in developing their wider professional networks (Wyckoff 2016). The evidence reviewed also suggests that doctoral graduates within STEM may have improved career outcomes including better prospects, higher salaries, more interesting work, and ultimately improved career trajectories (Wyckoff 2016, Hancock 2019).

2.4. Employees carrying doctorates in the engineering and physical sciences may be valuable to employers

Several studies explored the potential value of a doctoral student to an employer in both a UK and European context, however the evidence on this value was mixed. It is increasingly recognised that due to the scarcity of academic roles, STEM PhD graduates are likely to go into diverse professional and non-academic career paths (Hancock and Walsh 2016). Because of this, the potential value for doctoral students to potential employers is important to consider, and several studies have discussed this further. One study, based in Spain, pointed to the growing realisation that the technical skills developed by STEM doctorates are

[12] Chapter 4 provides a more detailed discussion of skills required and developed during doctoral training across the engineering and physical science sectors.

transferrable to non-academic careers and may bring significant value to non-academic employers (Garcia-Quevedo, Mas-Verdu et al. 2012). They suggested that doctoral students were important for facilitating R&D activities in firms, as well as ensuring that the firms can link to wider external networks within the scientific community, ultimately helping firms to acquire, assimilate and exploit external knowledge from academic contacts (Garcia-Quevedo 2012). This was supported by evidence from Finland that described three important reasons for companies to hire doctoral students including: that doctoral graduates bring knowledge and problem-solving skills, that doctoral graduates contribute through their networks, and that doctoral graduates can educate colleagues within the team through sharing knowledge gained during their doctorate (Naukkarinen 2016). However, the author suggests that there remains a lack of clarity on how to properly translate doctoral education into a career outside of academia.

Despite the potential value, employers may be reluctant to hire doctoral graduates. The Roberts Review conducted in 2002 suggested that employers were dissatisfied with the quality of doctoral graduates in the UK, although this evidence may be out-dated as the landscape has changed since then (Hancock and Walsh 2016). Specifically, the review identified a poor ability for STEM graduates to translate their knowledge to the commercial sector and a lack of adequate transferable skills. More recently, one study exploring graduate employability in Australia suggested that doctoral education may be less valuable for employment outside of academia as employers were found to rank a bachelor degree plus a masters more highly than a doctorate (Rayner and Papakonstantinou 2016). In addition, a doctorate may not provide added value if employers outside academia do not recognise the benefits of hiring an employee with a doctorate (Haapakorpi 2017). Authors of one UK-based study argued that STEM doctoral training may not adequately prepare students for their future professional lives, and therefore training needs to be adapted to provide value to non-academic employers (Hancock and Walsh 2016). Indeed, physics doctoral students in the US reported negative attitudes towards their doctorates when applying and interviewing for their careers in the private sector, including suggestions that they would be overqualified for the job (Giltner 2020). Furthermore, interviews with industry managers in the US revealed dissatisfaction with doctoral students in the workplace suggesting that doctoral graduates tended to overfocus on specific problems which may be irrelevant to task completion, as well as an unwillingness to make recommendations without extensive analysis (Giltner 2020).

Despite this, a survey conducted by Vitae of UK employers in 2009 found that one third of employers actively targeted doctorate graduates. In addition, employers generally rated doctoral graduates most highly in technical skills, problem solving, data analysis and project management (Vitae 2010). From the evidence in this review, it is challenging to identify why this contrast exists. The survey conducted by Vitae was not specific to doctoral graduates in the engineering and physical sciences, and therefore that may account for some of the discrepancy. In addition, the survey conducted by Vitae was conducted in the UK, suggesting that this may have more relevance to the UK context than the Australian or US based studies.

3. What are the eventual careers of engineering and physical sciences doctoral graduates?

In this chapter, we explore the evidence from the literature identified on the eventual careers of engineering and physical sciences doctoral graduates including:

- the eventual careers of engineering and physical sciences doctoral graduates;
- the factors that influence engineering and physical science doctoral graduates towards certain careers; and
- the factors that influence the hiring of doctoral graduates.

Studies included in this section were selected based on their overall applicability and relevance to the question of eventual careers of doctoral graduates in the engineering and physical sciences. The majority of studies reviewed were based in the US, and therefore this should be taken into account when considering the applicability of these findings in a UK context. However, several of the studies included in this section were from European countries including Finland, Germany, Portugal, Austria, Sweden, and Spain and therefore the results should offer some insights into doctoral education more broadly.

3.1. Key findings and summary of the evidence on the eventual careers of engineering and physical sciences doctoral graduates

Key finding	Number of sources	Number of sources based in UK	Strength of evidence	Applicability of findings to UK context
The evidence suggested that doctoral students in the engineering and physical sciences were likely to embark on both academic and non-academic positions, with differences between disciplines.	13	1	**High –** Nine sources were empirical studies, and two studies were literature reviews. The empirical sources used a mixture of primary (3) and secondary data (2) collection methods, mostly based on robust survey methods.	**Low/Moderate –** One study focused on the UK, 10 studies were based in the USA, one in Canada and one in Portugal.
Studies have highlighted a changing labour market for doctoral graduates	3	0	**Low** – Two studies were based on empirical survey data and one study was an opinion piece with no clear stated methodology. Despite empirical data supporting the key finding, there are few sources supporting this claim, making the strength of evidence low.	**Low** – Two studies were based in the USA and one in Canada.
Research interests may play a role in the career outcomes of doctoral graduates	6	0	**High** – All studies were empirical studies. All studies reported on findings from surveys, three of which were national surveys.	**Low** – Five studies were focused on the USA and one study focused on Canada.

Key finding	Number of sources	Number of sources based in UK	Strength of evidence	Applicability of findings to UK context
The academic research environment may deter doctoral students from pursuing a career in academia	15	2	**High** – There was one literature review and one conference proceeding about a program evaluation. The rest of these sources were from empirical studies. Three used secondary data from national surveys or publication databases, and the studies using primary data typically collected it from surveys or in-depth interviews.	**Moderate** – One study focused on the UK and another study included the UK in a comparative case study (alongside Norway and Sweden). Three studies focused on European countries (Austria, Portugal, Spain). The other studies focused on the North American region, with one study from Canada and eight from the USA. The two UK sources highlighted how an environment can act as a deterrent from entering an academic career and how important mental health is for PhD students.
There was mixed evidence on the role that gender may play in the eventual careers of doctoral graduates	5	0	**High** – Four studies were empirical studies using survey data and one used an ethnographic methodology.	**Low** – Four studies were focused on the north American context (one Canadian and three from the USA), and one study was European based (Finland).

3.2. The eventual careers of engineering and physical science doctoral graduates

The evidence suggested that doctoral students in the engineering and physical sciences were likely to embark on both academic and non-academic positions, with differences between disciplines.

For doctoral students in engineering, there was consistent evidence that most graduates find employment in industry or business. The studies reviewed found consistent evidence that most engineering doctoral students find employment in industry, although these studies were based in the US. (Marbouti, Lynch et al. 2014, Denton 2019, Hocker 2019, McGee 2019, Main and Wang 2020). A survey conducted in 2012 in the US found that 13.4% of doctoral recipients in engineering fields found employment in academia, whilst 72.9% found employment in industry or business, and 2.9% found employment in not-for-profit organisations (Choudhary 2015). Similarly, a survey conducted in 2015 by the National

Science Foundation (NSF), found that 14.4% of engineering US doctoral students had employment within academia while 72.1% found employment in industry or business (McGee 2019). This evidence is supported by more recent studies, which estimated that between 69% to 80% of engineering doctoral students found employment in the industry sector (Denton, Choe et al. 2019, Hocker 2019). It should however be noted that only one of the studies – Denton 2019 – looked at careers after a 5-year period and therefore this might have implications for eventual careers as even where individuals do enter into academia, they may transition to a different career later on. This evidence from the US was supported by one study in France, which found a decline in the proportion of engineering graduate students who started an academic career since 2010, with the majority of students finding work in industry or a business environment (Kövesi 2017).

For doctoral students in physics, there was some evidence that students may find employment in both academic and non-academic positions, although as before, studies were focussed on a US context. A study on the careers of physics doctoral students in the US found that the two most common initial career outcomes for graduates straight out of their doctorates were permanent positions in academia or the private sector, or postdoctoral positions (Mulvey 2020). Of the permanent positions, the majority of these were in the private sector, commonly in the fields of computer software, engineering and data science. Earlier studies in the US indicate that postdoctoral positions (either in academia or in government labs) were the most likely form of employment immediately following a physics doctorate (Anderson 2013, Mulvey 2014). One study – using publications in science journals as an indication of persistence within a research career – found that most (64%) doctoral graduates in the field of solar and space physics continued to publish 3 years after finishing their doctorate, suggesting a significant fraction remained within research (Moldwin 2016).

One study – based in Canada - explored the career outcomes of doctoral students in science and engineering more broadly and found that more than 60% of Canadian doctoral students were found to be employed in careers outside of academia, including industry, government, or non-governmental organisations (Chen 2019). Finally, although not specific to graduate outcomes of doctoral students within the engineering and physical sciences, there is information from the UK on the career outcomes of doctoral students: approximately 30% of doctoral students went into academic positions (teaching or research) and approximately 70% left academia, with 54% going into research roles (Hepi 2020).

Studies have highlighted a changing labour market for doctoral graduates, although these are based in the US

There was some evidence that there is a changing labour market for doctoral graduates, although studies were limited to a US context. Statistics from the US demonstrated that the proportion of science and engineering doctorates (out of all doctorates) had increased from 58% to 75% between 1974 and 2014 (McGee, Naphan-Kingery et al. 2019). However, during the same time period the number of tenure-track positions in the US had declined due to the fact that universities have increasingly relied on non-tenure track staff or part-time positions (McGee, Naphan-Kingery et al. 2019). A survey of the career preferences of science doctoral students in the US found that although academic careers (research and teaching) and careers within (industry and government) were commonly rated as the most attractive, other careers mentioned included science communication, science policy, non-university teaching, consulting and working for non-profit organisations (Sauermann and Roach 2012). Finally, evidence cited in Chen (2019) suggests that the changing labour market for doctoral graduates has not been met with a shift in training and career preparation.

3.3. The factors that influence engineering and physical doctoral graduates to pursue certain careers

The evidence suggests that research interests may play a role in the career outcomes of doctoral graduates

There was some evidence that research interests play a role in the career outcomes of doctoral graduates. One study - based in Canada - explored links between research environment and a student’s career preference. They found that where students were more directly involved in partnerships with non-academic institutions, they were more likely to indicate interest in careers outside of academia (Gemme and Gingras 2012). Despite this, the study reported that academia remained the favoured job destination among doctoral students, across the doctoral stages. Although there is likely to be a range of reasons that influence this, the study suggested that recognition within the department, such as small grants or scholarships, increased the academic aspirations of students to pursue a career in academia. The subject area in which the student is carrying out research or interested in, may also impact their early career. For example, doctoral students who had a greater interest in basic research, an increased desire for peer recognition, or a preference for choosing their own research topics, were suggested to be more likely to pursue a career in academia (Main 2020). On the other hand, students who had an interest in applied research, an interest in gaining professional experience or an interest in monetary returns, were suggested to be more likely to pursue careers outside of academia (Main 2020). This was supported by findings that explored the impact of a student’s dissertation topic on the type of employment secured by physics doctorate holders in the US one year after completion (Pold 2016). The study reported that students who undertook biological or nuclear physics were the most likely to accept a post-doctoral appointment compared to students in applied physics, plasma and fusion or optics who were more likely to accept a permanent position (Pold 2016). Although these studies provide useful insight, the reasons for graduates embarking on different careers are likely to be varied: graduate interest is likely to play a large role, but also job opportunity, and the degree to which graduates are aware of the available opportunities may also play a role.

Regarding academic career preferences specifically, one US study found that over half of students that were asked about their top choice for their first post-doctorate career placement, stated that they would prefer a research-intensive environment over a teaching intensive position (Pinheiro, Melkers et al. 2017). The study highlighted advisors as one potential factor in student preference, with advisors found to be more likely to suggest research intensive positions to those already interested in undertaking one, whereas where students were interested in teaching-intensive positions, advisors were likely to recommend either. This finding was supported by evidence that students across physics and chemistry felt that their advisors strongly encouraged academia research careers, whilst being less supporting of other career paths (Sauermann and Roach 2012). Other factors are also likely to be important: where students did accept a postdoc, the most cited influences were related to career goals, pursuing research interests and gaining valuable additional experience (Mulvey 2020).

The academic research environment may deter doctoral students from pursuing a career in academia

The evidence reviewed suggests that the academic research environment may deter doctoral students from pursuing a career in academia. For some doctoral graduates, not working in research is not a voluntary choice, but rather the result of limited job opportunities and unclear long term career prospects (Schwabe 2011). Didiano (2019) discussed the reasons why doctoral students may seek employment outside of academia, which included the limited number of permanent positions within academia, changing research interests of the doctoral students, and better paid positions in industry. Similarly, a survey of engineering and computer science US doctoral students and recent graduates found that 1 in 5 respondents were not open to the possibility of pursuing a career in academia (McGee 2019). Reasons for this included the pressures of working within the academic environment such as grant writing, imbalance of workload and salary, and internal politics within the academic environment (McGee, Naphan-Kingery et al. 2019). The authors also suggested that the increased salary of industry may attract students to industry roles. These findings were supported by survey and interview data acquired by Hocker (2019) whereby students in the US stated that grant writing and the pressure of financially supporting a laboratory were aspects of academic life that they considered negative. Another survey conducted in the US of students across the science disciplines found that the attractiveness of an academic career declined for both physics and chemistry doctoral students over the course of their doctoral education (Sauermann 2012). Possible reasons cited by the authors included that the students had started their doctorates with an overly positive view of academic life, and then changed their mind after experiencing the environment first-hand; that they had better opportunities of learning about career paths outside of academia or that they began to consider the job market at the end of their doctorate, and therefore felt less inclined to go for jobs that were considered scarce. Other studies have also commented on the decline in attractiveness of an academic career including limited job security and potential lack of opportunities (Main 2020). Furthermore, in light of the finding that the career aspirations of doctoral students may change during their doctorate, authors have suggested that there is a responsibility among the academic community to inform students of possible career options and prospects (Ginther 2015, Moldwin 2016). Doctoral students may have difficulty in identifying accessible positions and the requirements of industry, indicating that better support is needed (Kövesi 2017). Indeed, one study cited in Hancock (2016) suggested that career uncertainty may have negative impacts on the mental health of doctoral students. This was supported by literature cited in Su (2013) that suggested greater actions are required to facilitate doctoral students career transitions, including greater information for doctoral students on career prospects, in order for them to make informed career decisions.

Finally, the wider academic environment may influence the career choices of doctoral graduates. Greater interactions between industry, the private sector and universities may support doctoral students choosing careers in industry (Garcia-Quevedo 2012, Hottenrott 2017). This may in part be due to the networks that students adopt through these interactions (Germain-Alamartine 2020). In addition, advisors may provide support for students wanting to pursue a career within an academic research environment (Pinheiro, Melkers et al. 2017), and evidence has shown that where a student is exposed to a professor with high research performance, they are more likely to pursue a research role (Hottenrott 2017).

There was mixed evidence on the role that gender may play in the eventual careers of doctoral graduates

There was mixed evidence on the role that the gender of the doctoral candidate plays in the eventual careers of doctoral graduates. Some studies found that female doctoral students may be less likely to stay in academia than their male counterparts (Gonsalves 2018, Knaub 2018, Stockhard 2021). For example, data from the US found that women were less likely to persist within astronomy or astrophysics faculty positions than men (Gonsalves 2018). There may also be differences between career aspirations. A US-based survey reported differences between the career aspirations of male and female graduates, with female chemistry students less inclined than male chemistry students to aspire to professorships with an emphasis on research (as opposed to teaching) (Stockard 2021). Although it is not clear whether its directly related, the same study found that women reported fewer positive interactions with their advisors, an effect which was particularly pronounced for women belonging to an under-represented minority group. Furthermore, survey data from Finland suggested that female doctoral students tended to be more interested in non-academic careers than men (Knaub 2018). The evidence also suggests that along with gender, other characteristics or factors might have implications for the eventual careers of doctoral graduates. One study – based in the US – found that the employment sector entered by engineering doctoral students varied by factors such as sex, race/ethnicity, as well as demographic characteristics including the level of doctorate financial support received (Main and Wang 2020). Interestingly, the employment outcomes of previous cohorts also played a role: for example, doctoral students earning their degree from a department with a high proportion of students who had entered the government sector were also more likely themselves to work in that sector.

Despite these findings the evidence remains mixed. Another study based in the US found that female engineering doctoral students were more likely to stay within the academic environment and that male doctoral students were more likely to go into industry (Denton, Choe et al. 2019). Although the reasons for these differences in the literature remain unclear, the data used by Denton (2019) investigated career outcomes 5-6 years post-graduation, which may account for some difference between the studies. In addition, careers within academia were combined together (i.e. both research and teaching) and therefore the differences between female and male graduates may still apply.

4. What are the common skills requirements for doctoral graduates across all engineering and physical science sectors?

In this chapter, we explore the common skills requirements for doctoral graduates across the engineering and physical science sectors. Specifically, we focus on:

- The skills that doctoral students develop throughout their doctoral education; and
- Industry and sector demand for new doctoral skills.

Studies included in this section were selected based on their overall applicability and relevance to the common skills requirements for doctoral graduates in the engineering and physical sciences. Doctoral graduates go on to pursue careers in multiple sectors of the economy, including the charity/not-profit and public sector. However, our review mainly found evidence on the skills requirements for engineering and physical sciences doctoral students in academia or industry, with no reference to the skills required in other sectors of the economy. From the studies reviewed there was a limited number of UK-based studies, and therefore where relevant we have drawn insights from literature based elsewhere including studies from several European countries, the US, New Zealand, and Canada. The diversity of countries that were involved builds an informative picture of the global skills requirements for doctoral education and consistent trends were highlighted in the literature including the increasing focus on transferable skills, and increased diversity of career paths for doctoral graduates.

4.1. Key findings and summary of the evidence on the skills requirements for doctoral graduates across engineering and physical science sectors

Key finding	Number of sources	Number of sources based in UK	Strength of evidence	Applicability of findings to UK context
Doctoral education provides individuals with both ‘hard’ and ‘soft’ skills	4	0	**Low** – Two studies were empirical studies using surveys as the data collection method, the other two studies were a personal essay or an argumentative opinion piece. Despite the fact this finding is based on empirical evidence, the number of supporting studies is small, making the strength of evidence low.	**Low** – Two studies focused on the USA context, one studies on the EU’s Erasmus+ program (which could be slightly applicable to the UK context), and the final study included an online survey without a specificity of geographical breakdown of respondents.
Specialisation in certain skillsets may not adequately prepare students for varying and multidisciplinary environments	18	2	**High** – All sources listed are empirical studies, barring two which are a literature view and a personal essay from an experimental biologist. Data collection from these empirical studies are typically from survey design or consist of program evaluations.	**Moderate** – Two studies use the UK as part of a comparative study (France, Germany, Ireland, Italy, Netherlands, Portugal, UK) (Russia, Finland, Germany, Denmark, Jordan, UK). There are also three sources which have an EU regional perspective, two studies focused on Portugal, one study focused on Ireland, and one on Russia. Eight studies are focused on the USA context and one on Chile. There is a crossover of content between the UK and non-UK sources, as the UK sources highlight the importance of business knowledge and entrepreneurship, which also appears in non-UK sources.
The demand for skills is changing globally creating a need for new types of doctoral training	7	3	**Moderate** – Four studies are empirical studies, three are opinion pieces. The empirical studies collected their own primary data (through online surveys, in-depth interviews and focus groups).	**High** – Three sources are focused on the UK context. There are also two focused on the USA, one focused on Hong Kong and one on New Zealand. The themes which appear in the non-UK focused studies also show up strongly in the UK focused studies, both highlighting the changing demand for doctoral skills.

Key finding	Number of sources	Number of sources based in UK	Strength of evidence	Applicability of findings to UK context
The skills required from doctoral graduates vary by sector, although there are common skills between them	13	2	**Moderate** – The majority of these sources are empirical studies using their own primary data collection methods (mostly using in-depth interviews, but also collecting data from CVs). Four papers are either opinion pieces or have no mention of a formal methodology.	**Low** – Only one source is focused on the UK, and another mentions the UK as part of a comparative study (with Russia, Finland, Germany, Denmark and Jordan). This source and one other are European focused, with the other source comparing Sweden and Spain. The rest are North American focused (one paper focused on Canada and nine on the USA).

4.2. Doctoral education provides individuals with both ‘hard’ and ‘soft’ skills

During doctoral education, students are likely to develop both ‘hard’ and ‘soft’ skills. Hard skills typically refer to skills that are acquired through education or training and are generally measurable and easy to quantify (i.e. coding is a type of hard skill). On the other hand, ‘soft skills’ refer to interpersonal and emotional skills such as teamwork.

Hard skills developed during a doctorate include scientific writing, creating and delivering presentations, investigating systems and teaching, and one study suggested that STEM doctoral students are prepared with the specialist hard skills that industries typically seek out (Maxon 2019). One study highlighted that the technical skills doctoral students develop are in fact easily transferable to non-academic positions and are valuable to employers (Giltner 2020). For example, designing, writing, maintaining, and testing code is a specialised skill set that is highly sought after by industry (Voitenko, Gadasina et al. 2018). Soft skills developed during a doctorate involve skills such as ability to manage projects, ability to learn quickly, and creative thinking (Sinche, Layton et al. 2017). A large-scale survey of global doctoral researchers in science indicated that doctoral training developed transferable skills useful to both careers in research-intensive and non-research-intensive careers, suggesting that it adequately prepared students for both types of career path (Sinche, Layton et al. 2017).

Skills identified as less well-developed from a doctoral education included the ability to set a vision and goals, time management, ability to work in a team, ability to collaborate outside the organization, ability to manage others, and career planning and awareness skills. The survey broadly found that transferable skills were relevant to both research and non-research-intensive careers although some skills were favoured in one or the other: for example, research intensive careers were thought to favour creative thinking whereas non-research-intensive careers were thought to favour project management skills (Sinche, Layton et al. 2017).

To summarise the evidence Table 1 divides the skills mentioned in the literature into three categories: skills mentioned as gained in a doctorate within the literature and not mentioned as sector skills (academia and industry) in demand; skills mentioned as gained in a doctorate and mentioned as sector (academia and industry) skills in demand; and sector skills mentioned in demand but not mentioned as gained in a doctorate.

Table 1: Skills mentioned in the literature mapped against Vitae's Researcher Development Framework.

	Skills mentioned as gained in a doctorate in the literature, not mentioned as sector skills in demand	Skills mentioned as gained in a doctorate in the literature, and mentioned as sector skills in demand	Sector skills mentioned as in demand in the literature, not mentioned as gained in a doctorate
Engagement, influence and impact	**Teaching**	Communication (written and oral)	Cultural sensitivity & reflexivity
	Information sharing	Presentations	Conducting effective meetings
	Mutuality (through co-publication)		**Publications**
			Writing memos
Knowledge and intellectual abilities	Creativity	Problem solving	**Project management**
	Identify and systematically develop novel solutions	**Writing (general and scientific)**	**Business awareness, knowledge and management**
	Argumentation	**Specialised knowledge**	**Integration of innovation solutions with appropriate recognition of customer requirements**
	Derive realizable solutions not seen by others	Analytical skills	**Exceed the existing technical and scientific knowledge of the industry**
	Reasoning	Answering multidisciplinary research questions	People management
	Research methods	Critical reasoning	**Information, media and ICT literacy**
	Strategies for finding and processing new information	**Programming (designing, writing, maintaining, and testing codes)**	
	Identify systematic and chaotic errors		
	Investigating current systems		
	Ethics		
Research governance and organisation		**Designing experiments**	**Obtaining funding**
Personal effectiveness	Curiosity	Leadership	Teamwork
	Dedication	General management skills	Adaptability
	Determination	Flexibility	Collaborative working habits

Table 1: Skills mentioned in the literature mapped against Vitae's Researcher Development Framework.

	Skills mentioned as gained in a doctorate in the literature, not mentioned as sector skills in demand	**Skills mentioned as gained in a doctorate in the literature, and mentioned as sector skills in demand**	**Sector skills mentioned as in demand in the literature, not mentioned as gained in a doctorate**
	Perseverance	Independent working	Negotiation
	Resilience		Time management (and working to deadlines)
	Self-criticism		Accountability
			Providing/receiving constructive criticism
			Initiative
			Responsibility

Source: RAND Europe analysis. Skills in bold refer to hard skills and skills in normal font refer to soft skills. A full list of sources can be found in Annex C.

4.3. Specialisation in certain skillsets may not adequately prepare students for varying and multidisciplinary environments

There was some evidence that specialisation in certain skillsets may not adequately prepare students for the varied environments that they might go on to encounter. Two studies – one based in the US, and one based in Russia - highlighted that the specialisation in a narrow research field that doctoral students undertake when completing their studies may prevent graduates from developing soft skills and adequately preparing for multidisciplinary research environments (Watson 2011, Voitenko 2018). One study, which explored the skills development of doctoral students in the US, suggested that although a rotation format for education (comparable to the 1+3 doctoral programme in the UK)[13] was beneficial for introducing students to varying work contexts, it could potentially result in inconsistent growth in the development of their research skills (Maher, Gilmore et al. 2013).

One study suggested that specialisation in discipline-specific skills may be counterproductive in a private sector setting, as revealed in a US-based study that carried out interviews with industry managers, demonstrating resistance to hiring doctoral graduates (Giltner 2020). Industry managers stated several reasons for this including: that doctoral students spent time working on ideas that were not directly related to the company product; that doctoral students were sometimes overconfident in their own ability; and that doctoral students sometimes found it difficult to make decisions or recommendations when required (Giltner 2020). Indeed, one author recommended that for doctoral students to transition smoothly into the private sector, the development of a wider set of skills, such as team working, multidisciplinary working, working to deadlines, effective communication, people management, negotiation and providing and receiving criticism was required (Maxon 2019).

In addition, sometimes doctoral students have little experience working in a 'for profit' environment and therefore may lack the basic business knowledge needed to succeed in industry (Rodrigues, Freitas et al. 2018, Pisoni, Renouard et al. 2020). To succeed in industry, studies based in Europe and the US have suggested that doctoral graduates should improve their business management skills, like project management or balancing a budget (Cox, London et al. 2011, Cox, Zephirin et al. 2013, Knutas, Seffah et al. 2017, Rodrigues, Freitas et al. 2018). This increasing demand for business skills and knowledge is seen through the focus on entrepreneurship training during doctoral education in UK, US and European institutions, which teach doctoral students soft skills and basic business knowledge (McNabola and Coughlan 2014, Burylina, Sanger et al. 2016, Kövesi 2017, Mihai-Yiannaki, Varnava-Marouchou et al. 2017, Munoz 2020, Pisoni 2020). One such programme is the EU program EIT Digital, which runs a seminar on innovation and entrepreneurship where students learn about concepts including identifying alternative technical solutions to products already in the market, entrepreneurship and commercialization strategies, and advanced business models. (Pisoni, Renouard et al. 2020). Furthermore, it has been shown that where university laboratories encourage entrepreneurship, this results in an increasing number of inventions from the labs in

[13] 1+3 doctoral programme refers to a one year masters course coupled to a three-year doctorate.

question, as well as an increasing number of students joining start-up companies on finishing their doctorates (Roach 2017).

However, not all studies agree with the fact that doctoral students lack skills to succeed in industry. Authors have suggested that doctoral students do gain the skills, competencies and potential to meet employers' expectations (Tavares, Sin et al. 2019), such as presenting research; receiving and responding to feedback; problem solving/ troubleshooting problems (Burt 2017). Studies also highlighted the need for better communication to potential employers about the usefulness and transferability of many of the skills gained (Tavares 2019, Giltner 2020).

4.4. The demand for skills is changing globally creating a need for new types of doctoral training

The literature suggested that the demand for skills is changing, creating the need for new types of doctoral training. The broader environment in which students complete their doctoral education has shifted over time, creating demand for new skills. This demand for new skills may come from multiple sectors of the economy including the private sector, academic sector, charity sector, and the public sector. For example, areas highlighted include the advancement in communication and technology, the rise of citizen science, open science and increased policy around open access, the consideration of regulation and ethical procedures, and increasingly specialised and collaborative research that have altered the contemporary science research landscape (Hancock and Walsh 2016). This changes the demand for skills that doctoral students are expected to develop through doctoral training, as they may be more likely to work in multidisciplinary and industry focused environments. Whereas the traditional model of doctoral education might consider a doctoral student as a type of 'academic apprentice', focussing on developing specialised skills set and becoming an expert on a specific topic or field, the UK's research system now follows a 'knowledge economy' model where education in STEM, knowledge, and innovation are prerequisites for economic growth (Sampson and Comer 2011, Hancock 2019). As the academic and wider industry environment continues to shift, authors have suggested that students are more likely to consider doctoral education as an investment in their future career with opportunities to build their credentials and skills (Hutchings 2017, Hancock 2019).

As more doctoral students look for roles outside of academia, they must apply the skills developed in their doctoral education in this new environment. One author commented that doctoral students can often struggle to adapt to these new environments, although the transition can be aided if the company and managers are invested in developing the individual (Giltner 2020). The working demands of an industry position are likely to differ from a doctoral degree, and students may require knowledge in business, profits and consumer needs, meeting deadlines and wider relationship building. Horta (2018) describes how students are aware of the need to develop a broader set of skills to advance their careers and Halford (2011) suggests that individuals should consider how to use the skills gained during their doctoral education, such as problem-solving, outside of a traditional bench context.

4.5. The skills required from doctoral graduates vary by sector, although there are common skills between them

The literature highlighted the skills required from doctoral graduates vary across different sectors such as academia, research and development, and wider industry settings. Across the academic and industrial sectors, there was evidence of common skills required by both sectors, highlighted in Table 2.

Table 2. Skills valued in academia, industry and both sectors.

Skills identified in the literature as valued by the academic sector	Skills identified in the literature as valued by industry	Skills identified in the literature as valued by both academia and industry
Technical knowledge	Time management	Problem solving
Writing grant proposals	Undertaking unbiased work	Teaching
Autonomy	Leadership	Written communication
Mentorship skills	Multi and inter-disciplinary expertise	Research methods
	Business management	Critical thinking
	Commercialisation and technology transfer	Collaboration and teamworking
	Financial skills	Project management
	Strategy	
	Risk management	
	Engagement	
	Integrity	
	Responsibility	
	Networking	
	Creative thinking	
	Negotiation skills	

4.5.1. Skills specific to academia

Although there is evidence that some of these are acquired during doctoral education, there has been criticism that a doctorate may not adequately prepare graduates for academic roles in the US (Hocker 2019). Several of the skills highlighted in the literature as important to academia were also stated to be required by industry. However, some were only referenced in relation to an academic environment and included researcher autonomy, technical knowledge of particular principles (for example relating to physics), mentorship skills and writing grant proposals (Cox 2011, Porter 2018, Barnard 2020, Cox 2012).

4.5.2. Skills specific to Industry

The literature broadly distinguishes between Research & Development and wider industry. Several studies highlighted skills important to the industrial sector, with significant overlap between the different types of industry (Research & Development versus wider industry) and academia. In relation to industry alone, a range of skills were identified as being valuable. For example, US employers highlighted the need for multi-and interdisciplinary expertise when undertaking positions in engineering (Cox 2013). Similarly, business management, awareness of commercialisation and financial skills were all highlighted as important (Cox 2013, Sachani 2020, Cox 2012). Other skills specific to industry included leadership skills, problem solving with a focus on implementation and knowledge of customer needs, collaboration and teamwork (Knutas, Seffah et al. 2017, Germain-Alamartine and Moghadam-Saman 2020, Alvardo 2019). Furthermore, findings from interviews with industrial employers located in Europe suggest that doctoral graduates may lack adequate management or business skills, which are skills required to succeed in industry (Germain-Alamartine and Moghadam-Saman 2020). Indeed, Giltner (2020) suggested that there is a perceived mismatch between employer expectations and student skills. Despite these potential shortcomings, two studies highlighted that doctoral students' technical knowledge and research-related skills are important to employers (Alvarado 2019, Germain-Alamartine and Moghadam-Saman 2020). The Vitae Researcher Development Framework Engineering Lens also highlights skills across the four domains particularly relevant to engineering including in: research governance and organisation (strategy, project delivery and risk management), skills in engagement and impact (communication, influence and leadership, teamworking), knowledge (subject knowledge, research methods, critical thinking and problem solving) and personal effectiveness (integrity, responsibility, networking, time management) (Vitae 2014). Whilst not specific to doctoral education per se, reports have also highlighted the need for increased skills relating to digitisation, and the changing landscape that this is creating for engineering.[14] Updating the engineering and technical skills to accommodate this change has been stated as important to capitalise on this industrial revolution 4.0.

As well as the specific skills highlighted per sector, one author noted that doctoral students may have to develop skills after completing their doctoral education, and that getting used to uncertainty, learning how to adapt to change, and develop new skill sets for a job is part of being successful (Maxon 2019).

[14] https://www.raeng.org.uk/publications/reports/engineering-skills-for-the-future

5. What is the current community's opinion of the future of doctoral education, including any novel approaches?

In this chapter, we explore the evidence from the literature on the future of doctoral education, as well as any novel approaches identified including:

- recent trends in the current approach for doctoral education; and
- novel approaches to doctoral education that could address training gaps in the face of a changing research landscape.

Studies included in this section were selected based on their overall applicability and relevance to the future of doctoral education. It should be noted that although our review highlighted several areas of potential interest for the future of doctoral education and examples of novel approaches, there was limited evidence of the impact of these approaches being tested. From the studies reviewed there was a limited number of UK-based studies, and therefore where relevant we have drawn insights from literature based elsewhere including the US, Italy, Finland, Norway, Germany and Spain. Although the majority of findings did focus on the US, the diversity of countries involved and consistent themes that arose from the literature, suggested that there was moderate relevance to a UK context.

5.1. Key findings and summary of the evidence on the future of doctoral education in engineering and physical sciences

Key finding	Number of sources	Number of sources based in UK	Strength of evidence	Applicability of findings to UK context
There is a shift towards a transferable skills-based approach	18	5	**Moderate** – ten sources are empirical studies, there are four reviews and two opinion pieces. Then there are two papers collected which were not from the REA but directly relevant to discussions about STEM PhDs in the UK. Of the ten empirical studies surveys and interviews were used to collect primary data, but also student grades and assessments were reviewed to better understand the 'student experience' within certain PhD programs.	**Moderate** – There are five sources which mention the UK, only one of these mentions the UK in a comparative context (against France, Denmark, Germany, Ireland, Italy, Netherlands and Portugal). There are five sources focused on the USA, one on Canada and one on Chile. There is one which has a global perspective on practice-oriented curricula for STEM PhDs, and another which is a China versus Europe comparison. The rest are focused on European countries (Netherlands, Germany, Portugal, Sweden, Spain). The UK focused studies highlighted the importance of industry focused skills, potentially developed through industry sponsored PhDs or industry partnerships.
There is a need for tailored programmes to support student development during their doctoral education	17	1	**Moderate** – there were nine empirical studies, but the rest were more informal (with a personal essay, a generalised review of a training program or no methodology was stated). Empirical studies included one case study, two focus groups, four surveys, a program evaluation, or an analysis of CV data.	**Low** – One source was focused on the UK and an additional three were focused on other European countries (Finland, Germany and Spain). There were twelve sources from the USA, and one which had a broad global perspective on the issue of STEM graduates and employers' requirements. The UK focused study highlighted the importance of interdisciplinary discussion spaces for STEM PhD students.

Key finding	Number of sources	Number of sources based in UK	Strength of evidence	Applicability of findings to UK context
Greater support for doctoral students should be available to improve their doctoral experience	21	4	**High** – Seventeen studies are empirical studies. The other four studies include three papers which are written as narratives or have no specified methodologies, and one review of an initiative program evaluation.	**Moderate** – Four sources mention the UK, with three focusing specifically on the UK context and one using the UK as part of a comparison against Sweden and Norway. There are two sources which focus on Italy. Then fourteen are North American focused, with two focusing on Canada and twelve focusing on the USA. One study is an online survey which does not specify the breakdown of respondents by regions or countries. The UK studies focused on the importance of building industry partnerships, gaining industry experiences, and collegiate and supportive PhD cohorts.

5.2. There is a shift towards a transferable skills-based approach

In the UK, doctoral education has undergone transformation evolving from what was predominantly an apprentice model where a doctoral student would work closely alongside a supervisor, to a broader more comprehensive programme of doctoral training involving a supervisory team, and the institution more broadly (Spronken-Smith 2018, Willey 2019). There has been the introduction of cohort-based training through support for Centres for Doctoral Training. The research landscape is undergoing significant change and the evidence from the literature highlights several areas that could be a focus for improvement.

Gadasina (2016) recommended that within academia more activities are included that are not directly related to academic learning but instead focus on skills that are beneficial to doctoral students once they have graduated. These included skills such as supervision, negotiation, analysis, research and project management (Gadasina 2016).

Greater development of transferable skills would support doctoral students for future careers

As mentioned in Chapter 3, doctoral education provides students with transferrable skills that are valuable to employers across multiple sectors including academia. The expectations for engineering and physical sciences doctoral students varies depending on the sector they go on to be employed in and therefore the importance of providing students with the skills and opportunities to be successful in both academia and the private sector have been highlighted (Cox, London et al. 2011, Rodrigues, Freitas et al. 2018, Sachani 2020). For example, it has been suggested that students should gain both a ‘research mindset’, focussed on generating new knowledge, and a ‘development mindset’ focussing on rapid progress in problem-solving and profitable solutions (Giltner 2020). Future approaches to include greater links between the university and private sector in terms of career training or collaboration may be a way to develop these mindsets through exposure of students to the different environments (Giltner 2020).

In terms of the development of alternative or transferable skills, entrepreneurship education is important for enhancing levels of innovation from doctoral projects, increasing technology transfer, encouraging interpersonal and communication skills of the students, and making the recruitment of doctoral students more attractive to employers (Kövesi 2017, Muñoz, Guerra et al. 2020). Entrepreneurship education has a positive impact on students’ entrepreneurial intensions, and training could enhance the identification of practical applications of research (Muñoz, Guerra et al. 2020).

One study exploring how doctoral skills were adapted to the need of industrial employers stated that there was a need for increased relevance to industry within doctoral education. They stated that industrial doctoral programmes might be better suited to develop graduates for non-academic employers or similarly short-term industrial experience, or mandatory courses implemented with input from private sector employers would be useful ways to supplement the skills mismatch between academia and industry (Germain-Alamartine and Moghadam-Saman 2020). Interviewees from industry in the US also suggested that institutions should do more to cultivate students having a result-orientated mindset and engage students in more industrial type work during their doctoral education (Cox 2012).

Professional doctorates, cooperative doctorates, and industry placements may offer routes to doctoral students gaining skills other than research and subject-specific skills

The professional doctorate is focused on developing the research skills required within a professional context. The research carried out tends not to be a contribution to the knowledge base of a discipline, but more towards a contribution to the development of a professional domain (Bao, Kehm et al. 2018). The following competencies have been identified by one professional doctorate as required by students prior to graduation: a) envision, plan and conduct applied research and development activities; b) employ quantitative, qualitative, analytic and statistical techniques to technological problems; c) identify, comprehend, analyse, evaluate and synthesize research and professional practice; d) evaluate technologies and technology-related programs and leadership activities; e) Assess individual performance with, and understanding of, technology; f) function at a high level in one or more of the technology disciplines; g) apply advanced leadership practices to organizational challenges; and h) communicate effectively and employ constructive professional and interpersonal skills (Newton, Springer et al. 2019). In the UK, the number of professional doctorates has been increasing and has expanded into specialised subject areas (Smith 2015).

The industrial doctorate is an example of a model of university/industry cooperation, and a potential solution to providing engineering students with the knowledge and skills they need to progress within their careers (Grimm 2018). An example of this is the cooperative doctoral model employed by Synopsys Inc, and the Industrial Doctorate Centre between the

University of Bristol and University of Bath. The Industrial Doctorate Centre in Systems, part funded by EPSRC, is a collaboration between the University of Bristol and the University of Bath and offers an Engineering Doctorate (EngD) in Systems with the purpose of developing systems-thinking capabilities of future leaders in industry. A doctoral research project is undertaken as a partnership between the collaborating company and the IDC and researchers on the programme spend approximately 75% of their time in industry, and the focus of their research project is defined by the sponsoring company. Generally, these initiatives are thought to provide a positive picture of the transfer of knowledge between universities and industry and may help students develop wide ranging knowledge (Grimm 2018). To get the most out of industrial doctorates (both for the universities and industry) there should be exchange of information between the institutions involved, support to verify findings and facilitate implementation of results, academic faculty involved who have experience of working with industry, and good communication on the requirements of a doctorate (Kihlander, Nilsson et al. 2011). EPSRC has supported Industrial Doctoral Centres since 1992 and is one type of centre model supported through their Centres for Doctoral Training scheme.

Alternative models for doctoral outputs may be useful to consider

Given the importance of the thesis in earning a doctoral degree, the format of the thesis may be an important component to consider and provides a way for students to develop their writing and analytical skills. There are two primary formats for presenting a thesis, a monograph, and a thesis by publication (referred to in the UK as the alternative format). Within the UK, the monograph thesis is the traditional and most common format, however a thesis by publication has been gradually increasing in frequency. Germany commonly allows for a doctorate by published work, known as a cumulative dissertation, and this model has spread to other countries including the Netherlands, Sweden, and the US (Bao, Kehm et al. 2018). In certain circumstances, the UK also employs a similar model, characterised by enabling students to combine several articles published in peer-review or scientific journals into a coherent structure. However, this option is limited within the UK setting, and has tended to be awarded to select individuals. The model of doctorate by publication has attracted both praise and criticism. The benefits of a thesis by publication have included that student are better able to develop their writing-for-publication skills, reduce the time spent rewriting material from their thesis chapters for publication, and to increase their competitiveness when entering the academic job market.[15] However, criticism of the model includes a lack of consistency, differences in the definition of what constitutes a publication, as well as making the supervision of students more difficult. As such, many countries that offer this model have regulation in place (Bao 2018). One author also commented that doctoral curricula currently place too much weight on peer-reviewed publications, and that this was considered less important for industry-bound graduates (Isaacson 2019). They suggested that alternative standards for success beyond publications should be considered important, and that entrepreneurial endeavours and professional internships should be encouraged.

[15] As of 16th June 2021: https://www.bath.ac.uk/publications/submitting-an-alternative-format-thesis/attachments/submitting-an-alternative-format-thesis.pdf

5.3. There is a need for tailored programmes to support student development during their doctoral education

The literature reviewed suggested that there was a need for more tailored programmes to support student development. One study highlighted communication as particularly important, suggesting that increased opportunities were needed for students to communicate their work and the potential broader impact of their work on society (Dolgopolovas, Dagienė et al. 2020). There were some examples highlighted of tailored courses. One author highlighted that a course on training in effective leadership and decision-making whilst conducting meetings as being particularly influential (Maxon 2019). Some universities may also offer mandatory training in soft skills as evidenced by one German study (Hellweg 2011). Similar training exists in the UK.

Outside of formal training courses, other options have also been highlighted within the literature. For example, interdisciplinary discussion spaces for STEM students were suggested as an option to provide a space for promoting the political, economic, social and ethical questions that a researcher might face (Hancock and Walsh 2016). In addition, promoting reflection on these issues, and gaining research experience in a context outside of the university allows researchers to become more comfortable working with different stakeholders, as well as enabling the development of several skills such as improved science communication, the creative application of research skills and knowledge; and a deeper cultural understanding of how non-scientists view and use scientific evidence (Hancock and Walsh 2016).

Training to support graduates entering academia

The literature highlighted several challenges facing academic staff in the training and development of doctoral students and noted the importance of professional development for academic staff in order for them to be adequately prepared to meet these challenges. Challenges facing future faculty members include the increased diversity of student and faculty populations, an increase in the need for technology literacy and its potential application in teaching, limited funding and an increased focus on learning outcomes of students. These challenges could be mitigated with better teaching in communication with multiple audiences, learning to work in diverse group settings, and adopting technology to advance education (Cox, Zephirin et al. 2013). In addition, a concluding recommendation of one study was that academic staff should be better trained to function in cross-cultural, cross-race and cross-gender mentoring to ensure students get the support they need (Howell 2020). The literature also discussed the importance of training in teaching and learning communities or opportunities to network with faculty members and have been described as having a positive impact on the preparation of students for academic careers. In addition, one study exploring the institutional climate in preparing engineering doctoral students for academic careers stated that department culture also impacted whether students had teaching opportunities and that advisors and mentors had a role in supporting graduate students preparing for academic careers (Coso and Sekayi 2015).

Professional development programmes for future faculty provide doctoral students with a better understanding of faculty roles and responsibilities and may influence how future academic staff approach teaching (Connolly, Lee et al. 2018, Prevost, Vergara et al. 2018). One study highlighted that these programmes could address topics such as fostering diversity in the sciences, ethical conduct of research, academic job hunting and teaching development to enable doctoral students to gain the skills required to teach undergraduates (Connolly 2018). An evaluation of a high-engagement teaching programme in the US found that it had positively influenced how graduate students taught in the future with more than half the participants stating that they would go on to apply the principles and practices learnt during the programme to improve their teaching (Prevost, Vergara et al. 2018). Another study discussed the implementation of a mentoring programme aimed to promote competencies in communication, biomedical ethics, teamwork, altruism, multiculturalism and accountability. This was to support students in bioengineering and medical physics doctoral programmes to improve preparation for students who wanted to go into careers in translational research (Woods 2014). Furthermore, an academic careers workshop aimed at supporting graduate students to acquire the knowledge and skills required to write successful grant proposals in the US, supported students through mock review panels that reviewed successful and unsuccessful proposals (Hood 2013).

Tailored programmes to better prepare students for a career outside of academia

Certain programmes have also been established to support students with careers outside of academia. For example, The Mathematical Association of America has founded a programme for the preparation for industrial careers in the mathematical sciences by supporting students in engaging with research problems directly from industry (Alvarado and Price 2019). Another example is the BitBang course (an adaption of Nokia's management training course) which offers a way to teach the generic skills taught in corporate management training to researchers (Neuvo, Kuikka et al. 2017). There have also been programmes across Europe to facilitate the mobility of researchers into the private sector including programmes in Denmark, Portugal, Ireland, France and Spain (Garcia-Quevedo (2012). For example, in France the CIFRE (Industrial Agreements for Training through Research) programme aims to promote joint research projects through companies and public research laboratories by providing subsidies to companies that hire doctoral students who collaborate with public laboratories.[16] In Spain, the Torres Quevedo Programme provides grants to enable organisations such as business associations, private companies, or technology centres to hire doctoral graduates to develop industrial research projects, experimental developments or feasibility studies to support researchers to move into the private sector.[17] Approximately half of these researchers were found to remain within the private organisation following the end of the initial contract.[18]

Initiatives to support underrepresented groups

In addition, certain initiatives have been established to support different underrepresented or minority groups. For example, the iFEAT (Illinois Female Engineers in Academic Training) programme aimed to strengthen the applications of female engineering students applying to academic positions. This supported students through increasing their familiarity with the job-

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[16] As of 16th June 2021: https://stip.oecd.org/stip/policy-initiatives/2017%2Fdata%2FpolicyInitiatives%2F2372

[17] As of 16th June 2021: https://www.euraxess.es/jobs/funding/torres-quevedo-programme-ptq-2019-grants-recruiting-phds

[18] As of 16th June 2021: https://digital.csic.es/bitstream/10261/171924/1/innovation_capabilities_private_sector.pdf

hunting process, increasing participant confidence and supporting participants in the documentation required for job applications (Li, Mai et al. 2015). Another example is the ACADEME (Advancing Career in Academics with Diversity and Mentorship in Engineering) program in the US, aimed at preparing underrepresented minority doctoral students and post-docs for a career in engineering within academia through increasing their awareness of the requirements of the academy, advancing skills to do with teaching or research and increasing their networking opportunities (Cutright, Willits et al. 2018). Finally, one study explored the impact of a Dissertation Institute – an initiative in the US that provided underrepresented minorities with strategies to advance in their doctoral studies by providing students with writing partners and giving them the tools to create a writing plan (Cruz, Artiles et al. 2018).

5.4. Greater support for doctoral students should be available to improve their doctoral experience

Doctoral students need better careers advice during their doctorate

Evidence from the three studies included in our review suggests that doctoral students need better support with careers advice during their studies. Studies highlighted the need for increased career guidance for doctoral students, particularly as many students may not be sure which career they want to pursue at the time of undertaking their doctorates (Van Dusen 2014). One study, cited in Chen (2019), reported that there has been a greater push towards establishing career counselling resources for doctoral students. This is particularly important for students who will not follow the academic career path as students are often unable to get adequate advice from their academic supervisors to help them prepare for alternative careers to academia. One programme called the OPTIONS Program (Opportunities for PhDs: Transitions, Industry Options, Networking and Skills) was established at the University of Toronto in Canada to provide engineering doctoral students with weekly sessions to reflect on their personal qualities, strengths and interests to develop an individual development plan, highlight expertise and personal value, apply networking tools, and undertake practical activities such as cover letter writing and the development of interview skills (Didiano, Wilkinson et al. 2019). An evaluation of this programme found that the programme resulted in students being more optimistic and confident about their future. In addition, participants favoured the practical activities where they could obtain feedback (e.g. CV writing, informal interviews) (Didiano, Wilkinson et al. 2019). Furthermore, it was also suggested that careers counselling could support students in identifying the skills they had developed during their doctorate, particularly with regard to transferable skills that could be applicable to other sectors (Sinche 2017).

Greater links between private companies and universities are beneficial to graduates that seek to transition into industry

Six studies discussed the beneficial relationship between private companies and universities in maximising networking opportunities and facilitating the transition of doctoral students to industry. These studies were primarily focussed on a European context and are likely to be applicable to a UK context given the transition into industry is also an important route for doctoral students in the UK.

Evidence from the literature suggests that greater links between private companies and universities maximise networking opportunities and facilitate the transition of doctoral students to industry. To facilitate doctoral students' transition to industry, designing collaborative doctoral programmes (between industry and universities) that maximise the networking opportunities have been suggested as highly important (Germain-Alamartine, Ahoba-Sam et al. 2020). Cooperation between firms and universities is thought to assist the entry of researchers into firms, as well as reducing the potential information asymmetry (i.e. difference in the level of information) which can occur when hiring a doctoral graduate into the private sector by supporting firms to better understand the research background that doctoral students have and the environment they have come from (Garcia-Quevedo, Mas-Verdu et al. 2012). One study, based in Italy, investigated the factors that affected the propensity of doctoral students to create their own firms and found that where there were increased university-industry collaborations and where universities had policies regarding start-ups and spin-off companies, that this supported the creation of start-ups (Muscio and Ramaciotti 2019). The authors discussed that by exposing students to business problems, orientating student research towards a business context and enabling better recognition of market opportunities through industry-university collaboration students were better supported to create start-ups. Courses on entrepreneurship were also suggested by the authors as important in facilitating these activities (Muscio and Ramaciotti 2019). Finally, one study found that successful collaboration between universities and industry had resulted in inter-sectoral and inter-disciplinary transfer of knowledge between partners (Bosi, Mazzocchi et al. 2013). This was supported by universities engaging in activities including workshops, courses, and joint research projects and had wide ranging impacts including increased financial support for students through engagement with external stakeholders, improvements to employability and improved understanding of the social needs and requirements relating to research.

There are different formats these programmes can take in terms of the funding mechanism and time required in industry (Kitagawa 2014). In addition, research centres may increase the chances of positive outcomes even further by concentrating resources into a critical mass. The research centre format has been adopted in both the US and Australia with initiatives such as the Engineering Research Centres and the Industry-University Cooperative Research Centres in the US, and the Cooperative Research Centre programme in Australia. A non-centre based collaborative format has also been adopted in several countries across Europe, where students are supported in existing academic environments. One paper highlighted the EPSRC as developing a parallel model of both the centre and non-centre format with their EngD, and industrial CASE programmes. They suggested that each of the programmes expects doctoral researchers to work directly with industry, enabling students to gain industry-relevant skills and research experiences within an industry organisation (Kitagawa 2014).

Mentorship and group supervision may provide useful support to doctoral students during their studies

The evidence reviewed discussed the role of mentorship, group supervision, tailored support groups, and specific initiatives for underrepresented minorities in supporting doctoral students during their studies.

Several studies discussed the benefits of mentorship during a student's doctoral education (Cox 2011, Singe, Sheldon et al. 2021). Mentorship was stated as a strategy to facilitate students completing their doctoral education (Cox, London et al. 2011). It was also cited as being useful for promoting competency in students who travel abroad during their doctorate (Denney, Sánchez-Peña et al. 2015). Interviews with doctoral students in the US on their mentorship experiences found that mentors had helped students with careers advice and professional development (Singe, Sheldon et al. 2021). Furthermore, mentorship has also been found to impact student perceptions of research task difficulty (Hocker 2019). Relationships with advisors have been found to be critical in retaining doctoral students within their STEM doctoral programmes in the US (Ruud, Saclarides et al. 2018). Interestingly, two studies reported varying mentorship and advisor experiences for women and men, with women generally experiencing fewer positive interactions with their advisors (Ruud, Saclarides et al. 2018, Stockard 2021). Following this, two studies suggested that mentorship was particularly important to female doctoral students in providing them with support during their doctorate and into their future career (Dabney 2013, Gaule 2018).

Conducting a doctorate can be challenging. For example, a US-based study of doctoral engineering students highlighted that over half the students experienced mental health issues during their doctoral education (Hocker 2019). Peer mentorship has been cited as providing a way to enable a diverse, inclusive and supportive environment which may improve the doctoral experience (Bôas Fávero, Moran et al. 2018, Hocker 2019, Barthelemy, McCormick et al. 2020). In a chemical engineering doctoral program in the US, groups of peers would meet once a week for social or academic activities with a survey of participants indicating that the program had increased department inclusivity and community; strengthened peer social bonds; and improved coursework and research outcomes. Student-student collaboration was also an important method of support for women studying in a US astronomy graduate programme (Barthelemy, McCormick et al. 2020).

Groups to support students during their doctoral education have also been successful. For example, one study found that an informal support group of doctoral students in the US supported students during their dissertation writing through encouraging motivation, sharing knowledge of dissertation-related processes and providing personal support to one another during the process (Denman, Corrales et al. 2018). One UK based study suggested group supervision as a way to improve doctoral student support, providing a collegiate atmosphere between students and enabling shared experiences and learning (Hutchings 2017).

6. Conclusions

Doctoral education is intended to train students to conduct high-quality research. Historically, this research was mainly focused on academic questions that aimed to advance knowledge, and the application of this knowledge was a secondary outcome. However, in recent decades the applicability of research ideas into innovative solutions has taken centre stage, as there is more immediate value to society from the research conducted. This is specifically the case in fields of research that are more applicable, such as engineering.

This study implemented an REA to explore the value of doctoral education in the engineering and physical sciences including the benefits of undertaking a doctorate; the sectors that doctoral graduates enter; the skills requirements for graduates and how doctoral education can best transition and support students going forwards.

The value of doctoral education in engineering and physical sciences

The evidence from the reviewed literature indicates that doctoral education provides value in several ways and is beneficial to the individual, potential employers, and society more broadly. The literature suggests that doctoral students play an important role in carrying out novel research, ultimately contributing to the creation and transfer of knowledge, and the wider economy. In the field of engineering and physical sciences, doctoral students are trained to work on research areas with immediate applications to society such as green energy and robotics. Doctoral students not only generate value through the research they conduct but also the skills they acquire. The development of both technical and transferable skills enables the students to traverse a broad range of careers. Our literature review found that doctoral students develop a wide range of transferable skills that are sought after by potential employers, including critical reasoning, problem solving, communication, and leadership. As doctoral students enter employment, they can apply these skills to a range of environments and subject matter making them valuable to their employers. However, several skills considered important to potential employers were also highlighted as potentially missing from a doctoral education including skills in business awareness, time management and people management. This might suggest why some of the literature reported that employers sometimes portrayed negative attitudes towards the hiring of doctoral students. Despite this, a survey conducted by Vitae suggested that one third of UK employers actively target doctoral graduates, suggesting that there is high demand from certain types of employers. Furthermore, studies have suggested that doctoral students are not always aware of the transferable skills that they develop throughout their degree, which may impact their ability to secure an industry position. Similarly, employers outside of academia do not always recognise the benefits of hiring an employee with a doctorate. Increased careers support to doctoral students, highlighting the skills gained during their doctorate, may support students to effectively communicate these skills to employers.

Eventual careers of engineering and physical sciences doctoral graduates

The evidence demonstrates that doctoral graduates within engineering and physical sciences go into a range of careers. There was consistent evidence that the most common form of employment for engineering and physical science graduates was industry. In Canada and France, most doctoral graduates in the engineering and physical sciences pursued non-academic careers. In the US, engineering doctoral graduates commonly found employment in industry or business whereas physics graduates were more likely to undertake post-doctoral positions in academia. Although the majority of studies in this REA on career outcomes were based on employment outcomes from the US, there was evidence that these patterns appeared true more broadly.

Several factors were suggested as important in influencing doctoral graduates to pursue certain careers. For example, connections and collaboration with industry during doctoral studies may contribute to students' interests in careers outside of academia. Students with greater interest in basic research and peer recognition are more likely to pursue a career in academia and those with an interest in applied research and an interest in gaining professional experience are more likely to pursue careers outside of academia. In addition, Doctoral students may seek employment outside of academia due to the limited number of permanent positions within academia, changing research interests, imbalance of workload and salary, better paid positions in industry, pressures of working in an academic environment (e.g. grant writing), and the politics of academia.

Skills requirements for doctoral students in engineering and physical sciences

The diverse range of potential careers also creates a diverse range of skills requirements for graduate students. Doctoral students develop technical skills which are valuable to employers. In particular, transferable skills – relevant to diverse sectors and job roles – were stated as being highly relevant to the landscape today. Several skills were highlighted as important to both academic and industry sectors including written communication, problem solving and critical thinking, suggesting that training in particular skillsets are likely to support doctoral graduates in the diverse career paths they enter. Although this review highlighted common skills requirements for doctoral graduates, it should also be noted that due to the scope and size of this REA we picked up limited evidence on the skills requirements across particular sectors such as the charity and not-for-profit sector. Although far fewer doctoral students enter these careers, further evidence on the requirements of these sectors would support the transition of doctoral training. Similarly, several of the studies referred to the skills required by industry more broadly as opposed to the specific requirements of certain industrial sectors. Although this is still informative, further studies carrying out research in this area should seek to determine the requirements across specific job roles to better inform the potential requirements for doctoral education.

The future of doctoral education in engineering and physical sciences

Given the importance of transferable skills described in the literature across sectors it is perhaps unsurprising that community opinion on the future of doctoral education suggested a shift towards an increasing transferable skills-based approach in order to support doctoral students as they embark on their careers. The literature suggests that professional doctorates may help bridge the gap between academia and industry and benefit all parties involved, by contributing to the knowledge base with direct application. Multiple studies have assessed the role of tailored programmes in improving the outcome of doctoral education. However, most of these studies have focused on single centres in the US. Although some of these pilots may not be relevant to the UK context - such as those focused on teaching undergraduates (something that is far less common in UK) - others may be relevant, particularly those on increasing diversity of doctoral cohorts. Initiatives to support underrepresented groups are also increasingly important as we continue to aim for a more inclusive society and UKRI, alongside other funders, are undertaking large efforts to increase their efforts in this area. Additional training may support doctorate students to transition smoothly into their future careers. The literature reviewed here highlighted examples of training both to support students remaining in academia, as well as to support students entering non-academic careers. Finally, studies highlighted that greater support is needed to improve the doctoral experience for students. Better careers advice may decrease the uncertainty that many students feel when undertaking their doctorate. Similarly, greater links between private companies and industry may support graduates who ultimately seek to transition into industry.

Existing gaps in the literature

Whilst this REA provides insight into the value of doctoral engineering in the engineering and physical sciences, there are several limitations to note. Firstly, this REA was not a systematic review of the literature, and therefore it is possible that relevant literature was not included in this review. There are important gaps in the existing literature that need to be addressed to better understand the value of doctoral education in the engineering and physical sciences in the UK. Across the research questions, there was very limited evidence relating to the UK across the research questions, with studies focussing on a US or European context. Whilst there are studies exploring a UK context, this often looks at doctoral education as a whole, and therefore further work exploring the outcomes and potential impact of doctoral education across the varying sectors would be beneficial. There were other areas where this review is limited. Whilst we did find evidence relating to the skills requirements in both the academia and industrial sectors, there was limited evidence of the skills requirements for sectors such as the charity sector. Similarly, where the literature assessed the outcomes of doctoral education and any novel approaches taken, there was limited evidence of any evaluation of impact.

Finally, it should be noted that the literature often lags behind current practice. For example, approaches for the future of doctoral education suggest a greater emphasis on transferable skills, and industrial-academic partnerships. This is something that exists in the UK. The EPSRC offer collaborative training where up to 50% of the student's funding may be provided by a partner organisation based in the private, public, or civil society sectors supporting students to work on projects spanning these sectors. Similarly, EPSRC offer work placements and internships to give students a chance to develop their doctoral training further, or to gain valuable transferable skills, and EPSRC Centres for Doctoral Training aim to bring together diverse expertise to provide doctoral students with the skills and knowledge to tackle diverse societal challenges. Whilst this study provides a useful overview of doctoral training in the engineering and physical sciences and has brought together evidence both from a UK and global context, it is clear that more work is needed to evaluate and inform doctoral training in the UK.

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Annex A. Methodological approach

To better understand the evidence available on doctoral education in engineering and physical sciences, we conducted a Rapid Evidence Assessment (REA) to answer the following research questions:

1) What is the value of an engineering and physical sciences doctoral education?
2) What common skills are required from doctoral graduates across the engineering and physical sciences sectors?
3) What are the eventual career pathways for engineering and physical sciences doctoral graduates?
4) What is the current community opinion on the future of doctoral education, including any novel approaches?

6.1. Scoping interviews

In order to inform the research questions and research design, we conducted a series of scoping interviews with different experts in higher education policy (Table 3). The interviews explored different aspects to consider in terms of the value sources to include in our study. Interviews were conducted over the telephone or using Microsoft Teams with duration of 30-45 minutes. The protocol used for these interviews can be found in Annex B.

Table 3 Interviewees for the scoping interviews

Interviewee	Organisation
Benjamin Hunt	Office for Students
Janet Metcalfe	Vitae
Nick Hillman	Higher Education Policy Institute
Douglas Halliday	UK Council for Graduate Education

6.2. Rapid evidence assessment

REAs are reviews of the literature that are robust and reproducible in their approach, but also make some concessions as compared to a systematic review to ensure that they are efficient in terms of time and resources required. An REA includes four stages: literature search, literature screening, data extraction, and synthesis. These are described in detailed in the sections below.

6.2.1. Search strategy

We developed and piloted a comprehensive search strategy, focusing on doctoral education in engineering and physical sciences together with RAND's specialist in-house librarians. We ran searches in Web of Science (Box 5), Scopus (Box 6) and ERIC (Education Resources Information Center) (Box 7). The search was limited to article published in English between 1st January 2011 and 17th May 2021, resulting in 6145 articles. After removing duplicates, these searches resulted in 4455 articles.

Box 5 Search string used for Web of Science

TS=(engineering OR "physical science*" OR “physics” OR electronic* OR computer* OR chemi* OR math* OR STEM OR manufacturing OR technology) AND TS=("doctoral training" OR "doctoral education" OR "doctoral studies" OR "PhD" OR "Doctor of Philosophy" OR "post-graduate training" OR "doctoral student" OR doctorate OR PGR OR post-graduate researcher or EngD OR "level 8")
AND
(TS=(value* OR worth OR benefit* OR advantage* OR impact*)
OR
TS=(skill* OR competenc* OR expertise OR capabilit*)
OR
TS=(career* OR prospect* OR job OR jobs OR role OR roles OR destination OR sector* OR profession* OR occupation* OR employment)
OR
TS=(future OR novel OR recommendation OR approach))
NOT
TS=("stem cell*") OR TS=(phase-type distributions) OR TS=(Plant growth regulators) OR TS=(Panax ginseng residue)

Box 6 Search string used for Scopus

TITLE-ABS(engineering OR "physical science*" OR “physics” OR electronic* OR computer* OR chemi* OR math* OR STEM OR manufacturing OR technology) AND TITLE-ABS("doctoral training" OR "doctoral education" OR "doctoral studies" OR "PhD" OR "Doctor of Philosophy" OR "post-graduate training" OR "doctoral student" OR "doctorate" OR PGR OR "post-graduate researcher" OR EngD OR "level 8")
AND
(TITLE-ABS(value* OR worth OR benefit* OR advantage* OR impact*)
OR
TITLE-ABS(skill* OR competenc* OR expertise OR capabilit*)
OR
TITLE-ABS(career* OR prospect* OR job OR jobs OR role OR roles OR destination OR sector* OR profession* OR occupation* OR employment)
OR
TITLE-ABS(future OR novel OR recommendation OR approach))
NOT
TITLE-ABS("stem cell*") OR TITLE-ABS("phase-type distributions") OR TITLE-ABS("Plant growth regulators") OR TITLE-ABS("Panax ginseng residue")

Box 7 Search string used for ERIC

((TI(engineering OR "physical science*" OR “physics” OR electronic* OR computer* OR chemi* OR math* OR STEM OR manufacturing OR technology) OR AB(engineering OR "physical science*" OR electronic* OR computer* OR chemi* OR math* OR STEM OR manufacturing OR technology)) AND (TI("doctoral training" OR "doctoral education" OR "doctoral studies" OR "PhD" OR "Doctor of Philosophy" OR "post-graduate training" OR "doctoral student" OR "doctorate" OR PGR OR post-graduate researcher or EngD OR "level 8") OR AB("doctoral training" OR "doctoral education" OR "doctoral studies" OR "PhD" OR "Doctor of Philosophy" OR "post-graduate training" OR "post-doctoral studies" OR "doctoral student" OR "doctorate" OR PGR OR post-graduate researcher or EngD OR "level 8")))   AND   (TI(value* OR worth OR benefit* OR advantage* OR impact*) OR AB(value* OR worth OR benefit* OR advantage* OR impact*) OR TI(skill* OR competenc* OR expertise OR capabilit*) OR AB(skill* OR competenc* OR expertise OR capabilit*) OR TI(career* OR prospect* OR job OR jobs OR role OR roles OR destination OR sector* OR profession* OR occupation* OR employment) OR AB(career* OR prospect* OR job OR jobs OR role OR roles OR destination OR sector* OR profession* OR occupation* OR employment) OR TI(future OR novel OR recommendation OR approach) OR AB(future OR novel OR recommendation OR approach))

6.2.2. Screening

Once the literature search was completed, articles captured by the search were subject to title and abstract screening to determine their selection for the study. Article selection was based on a set of predefined inclusion and exclusion criteria relating to publication year and language, location, discipline, study type, and situation (for further details see Table 4).

Table 4 Inclusion and exclusion criteria used in the study

Criteria	Include	Exclude	Rationale
Publication date	2011- 2021	Pre-2010	The approach to doctoral training has changed over the last decades in the UK, with a more cohort-approach than an individualised approach. Therefore, we propose to include literature that reflects this change as it will be the most relevant to the study.
Location	All countries. Priority will be given to UK-based evidence, with Europe, US, Canada and Australia having second preference, and evidence from countries outside of this where relevant.	N/A	Priority will be given to UK-based evidence with international sources and examples used where they are relevant to the UK higher education system.
Language	English	Non-English	It is expected that literature searches applying the English-language search terms (presented later in this section) will yield mostly English-language sources.
Study type	Peer-reviewed journal articles, PhD theses; conference proceedings; grey literature		We believe the literature in this area will not be extensive and the majority will not be peer-reviewed publications. Therefore, we will not exclude publication types.

Discipline	Primarily literature from the engineering and physical sciences, or where a discipline is not specified, and insight can be gained.	All other academic disciplines unless cross disciplinary insights presented.	The review is seeking specifically to address the topic of doctoral education in engineering and physical sciences.
Situation	Doctoral careers and impact	Graduate training/ post-doc training, training outside of the research sector.	The review is seeking specifically to address the topic of doctoral education in engineering and physical sciences and the impact of the skills developed through a PhD on graduates' careers.

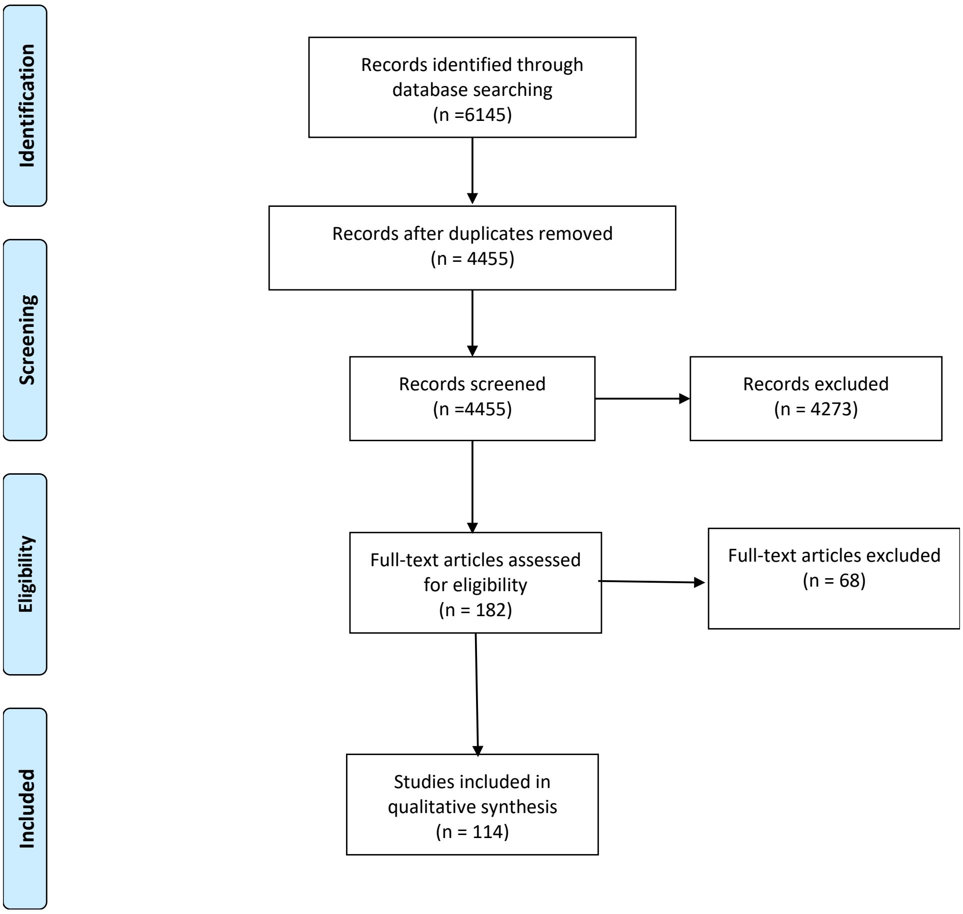
Title and abstract screening

The searches described above resulted in 6145 articles, all of which were screened by title and abstract. A pilot screening was undertaken by two researchers (CS and IF) in which they both screened the same 30 articles to ensure that the inclusion and exclusion criteria were applied consistently. The researchers reviewed each title and abstract, and assigned a rating of include, exclude or maybe for each article, without knowing how the other reviewer rated the article. Once both researchers had finished their screen, articles for which reviewers assigned different ratings were discussed until consensus was reached, and in cases of disagreement a third researcher (DR) was consulted to assist with decision-making. Articles were then distributed across the research team. Articles that were classified as includes or maybe were screened by a second reviewer, and in cases of disagreement, these were discussed until consensus was reached. This stage resulted in 182 articles continuing to full text screening, and 4273 articles being excluded, for an inclusion rate at this stage of approximately 3%.

Full text screening

All 182 articles that were selected for full text screening based on title and abstracts were retrieved and reviewed to assess whether they should proceed to extraction. Four researchers (CdA, CS, DR and IF) conducted the full text screening of the articles, with each article being reviewed by one researcher. Based on this screening, 114 of the 182 articles were included for extraction, while 48 articles were excluded based on their lack of relevance to the research questions. An overview of the number of articles that were identified, screened and included in the review is shown in Figure 1.

Figure 1 PRISMA diagram for the REA



6.2.3. Extraction

A total of 114 articles were included for extraction. Four researchers (CdA, CS, DR and IF) conducted the extraction using an extraction template in Excel. The template captured information about the design of the study, the context of the study and information of each study relevant to answering each research question. Given the broad inclusion with regards to study designs and the large number of sources included, in-depth quality assessment of each study was not feasible. We therefore applied a set of qualitative quality assessment questions that were applicable to all study designs, relating to the strengths and limitations of the study.[19] This information was combined with other extracted data, such as study design and sample size, to evaluate the contribution of each study to the evidence base. The extraction template captured information as it was reported in each article, and also provided space for researchers to reflect on the relevance of the study to our research questions and other comments on the study. The fields of the extraction template are provided in Box 8.

[19] These included questions on strengths, limitations and comments on overall study quality.

Box 8 Fields of the extraction template for the REA

Study characteristics

- Reference
- Brief summary
- Publication type
- Study type
- Methodology type
- Methodology
- Country
- Context

Value of an engineering and physical sciences PhD

- Perceived value
    - Value to the individual
    - Value to employers
    - Value to society
    - Other
- Actual value
    - Value to the individual
    - Value to employers
    - Value to society
    - Other

Common skills requirements

- Technical skills
- Transferable skills
- Other

Eventual careers

- Academic/University
- Private sector
- Non-profit/Charity
- Public sector
- Other

Future of doctoral education

- Novel approaches
- Approaches taken elsewhere
- Other

Evidence in gaps and limitations

- Future research needs/gaps in knowledge
- Limitations
- Strengths
- Comments on quality

Other comments

6.2.4. Additional sources

In addition to sources identified through the literature review, an additional 25 sources were recommended by experts. Where these were relevant to the study, and not already included in the original literature review, these were added to our list of articles for further analysis. In total, this provided an additional 12 studies.

6.3. Analysis and synthesis reflected

Once all included articles were extracted, we conducted an internal workshop with the research team and a representative of EPSRC to ensure that our analysis the needs of EPSRC in the context of the broader review of doctoral education they are carrying out. The workshop was carried out remotely using MURAL[20], a digital workspace for visual collaboration. The different statements that were identified in an initial analysis phase, were mapped against the research questions to facilitate identifying key messages as well as develop conclusions from the literature review.

6.4. Strengths and limitations of the approach

The strengths of the REA lie in our inclusion of global literature, which allows us to gain insight into different approaches used for doctoral training in engineering and physical sciences worldwide as well as the career outcomes and skills required for doctoral graduates across multiple countries. An REA provides a systematic and robust approach to reviewing the evidence. In addition, the timeframe considered enables us to capture evidence on how doctoral training has been changing in response to policy trends that have occurred over the last decade, which have led to doctoral education as it occurs nowadays, and how adaptations are needed to meet the policy and skills requirements going forwards. Lastly, we used three different databases (Web of Science, ERIC and Scopus), ensuring that we could capture a broader range of relevant literature across the research disciplines.

However, there are several limitations to the REA. Firstly, studies looking at careers outcomes for doctoral graduates usually cover a wide range of disciplines. However, our search strategy was designed to capture literature focusing specifically on engineering and physical sciences and therefore if the terms engineering and/or physical sciences were not included in the title or abstract of a paper, these would not have been picked up. The scoping interviews helped mitigate this risk by asking interviewees, who are experts in higher education policy, about potential literature to include in the study. Secondly, the study was limited to publications in English. Although this did return a good number of articles to review, it is possible that some articles (especially opinion pieces, commentary, interviews or policy documents) were missed. Finally, when conducting an REA, the search terms are restricted more so than when conducting a systematic literature review. Therefore, whilst we tried to be comprehensive when compiling the search terms, it is possible that certain sources were neglected.

[20] MURAL is a digital workspace for visual collaboration, that multiple people can access simultaneously and work together on a specific topic. https://www.mural.co/

Annex B. Protocol for scoping interviews

Introduction

Thank you for speaking with us. RAND Europe, in partnership with Vitae, has been commissioned by the EPSRC to gather evidence on the value of engineering and physical sciences doctoral education. Part of this project will involve a literature review, which will seek to gather evidence on the value of doctoral education, common skills requirements, eventual careers of graduates and potential improvements for the future of doctoral education. The EPSRC is currently undertaking a two-stage review of their investment in doctoral education. This work will feed into the first stage of the review which will gather evidence on doctoral education, and build recommendations

To support the ongoing literature review, we are conducting several scoping interviews with relevant stakeholders to gather additional input on the scoping of the exercise as well as relevant documentation that we may wish to consider.

Interview questions

Background

1. Could you tell us about your current role and how it relates to doctoral education?

Questions

2. If you were conducting a review on the value of doctoral education what would be the main aspects that you would consider important?
3. A previous review on the value of doctoral education in the economic and social sciences found little evidence on the value of doctoral education relating to these disciplines specifically. Is there anything you would consider relevant to the value of doctoral education within the engineering and physical sciences specifically?
4. Two of the research questions will focus on common skills requirements, and eventual careers, of doctoral students. Are there any other outcomes that you think might be important to consider?
5. The EPSRC are interested in how the doctoral education experience can be improved. Where do you see the main areas of improvement being?
    a. Is there anything that would be relevant to the physical and engineering sciences specifically?
6. The EPSRC are interested in collecting opinion on any novel approaches to the future of doctoral education. What sorts of things do you think might be important to consider when thinking about the future of doctoral education?

Final thoughts

7. Is there anything else we have not discussed that you think would be good to mention?
8. Are there any sources you think it would be particularly good to reference in relation to these research questions?

Annex C. Table of skills

Skill	Sources
Communication (written and oral)	Voitenko, S. Gadasina, L. Sørensen, L. 2018 The need for soft skills for ph.d.’s in software engineering Conference Proceedings Watson, J. Lyons, J. S. Asee, 2011 AC 2011-363: A SURVEY OF ESSENTIAL SKILLS FOR PHD ENGINEERS IN INDUSTRY Book Section Cox, M. F. London, J. S. Ahn, B. Zhu, J. Torres-Ayala, A. T. Frazier, S. Cekic, O. 2011 Attributes of success for engineering Ph.D.s: Perspectives from academia and industry Conference Proceedings Denney, L. B. Sánchez-Peña, M. Main, J. B. 2015 Examining how international experiences promote global competency among engineering graduate students Conference Proceedings Cox, M. F. Zephirin, T. Sambamurthy, N. Ahn, B. London, J. Cekic, O. Torres, A. Zhu, J. B. 2013 Curriculum Vitae Analyses of Engineering Ph.D.s Working in Academia and Industry Journal Article International Journal of Engineering Education 29 1205-1221 Knutas, A. Seffah, A. Sorensen, L. Sozykin, A. Al-Zaghoul, F. Abran, A. 2017 Crossing the Borders and the Cultural Gaps for Educating PhDs in Software Engineering Book Section Dolgopolovas, V. Dagienė, V. Jevsikova, T. 2020 Student-Centered Graduate STEM Education Integrated by Computing: An Insight into the Experiences and Expectations of Doctoral Students Serial Sampson, Kaylene Comer, Keith 2011 Engineering Research Teams: The Role of Social Networks in the Formation of Research Skills for Postgraduate Students Journal Article International Journal for the Scholarship of Teaching and Learning 5 Hancock, S. 2019 A future in the knowledge economy? Analysing the career strategies of doctoral scientists through the principles of game theory Journal Article Higher Education 78 33-49 Horta, H. 2018 PhD students' self-perception of skills and career plans while in doctoral programs: are they associated? Journal Article Asia Pacific Education Review 19 211-228 Wyckoff, A. 2016 The Science and Technology Labor Force The Value of Doctorate Holders and Development of Professional Careers Foreword Book Munoz, C. A. Guerra, M. E. Mosey, S. 2020 The potential impact of entrepreneurship education on doctoral students within the non-commercial research environment in Chile Journal Article Studies in Higher Education 45 492-510 Tavares, O., C. Sin, S. Cardoso and D. Soares 2019 ARE INDUSTRIAL DOCTORATES CAPABLE OF OVERCOMING SKILLS MISMATCH? Book Section Didiano, T. J. Wilkinson, L. Turner, J. Franklin, M. Anderson, J. H. Bussmann, M. Reeve, D. Audet, J. 2019 I have a PhD! Now what? A Program to prepare engineering PhDs and post-doctoral fellows for diverse career options Conference Proceedings Kövesi, K. 2017 Entrepreneurship education for PhD students in engineering sciences Conference Proceedings Gonsalves, A. J. 2018 Exploring how gender figures the identity trajectories of two doctoral students in observational astrophysics Journal Article Physical Review Physics Education Research 14 Abe, Y. Watanabe, S. P. 2012 Some thoughts on implementing US physics doctoral education in Japanese universities Journal Article Asia Pacific Education Review 13 403-415 Sachani, S. S. 2020 Best of both worlds: A career in technology transfer and business development Journal Article Developmental Biology 459 30-32

Skill	Sources
	Woods, K. V. Peek, K. E. Richards-Kortum, R. 2014 Mentoring by Design: Integrating Medical Professional Competencies into Bioengineering and Medical Physics Graduate Training Journal Article Journal of Cancer Education 29 680-688 Parker, M. C. Tsugawa-Nieves, M. A. Satterfield, D. Perkins, H. Bahnson, M. Cass, C. Kirn, A. Ieee, 2019 Engineering Doctoral Student Perceptions of Research Task Difficulty and the Student-Advisor Relationship Book Section Hellweg, C. E.; Spitta, L. F.; Kopp, K.; Schmitz, C.; Reitz, G.; Gerzer, R. (2016): Evaluation of an international doctoral educational program in space life sciences: The Helmholtz Space Life Sciences Research School (SpaceLife) in Germany. In Advances in Space Research 57 (1), pp. 378–397. DOI: 10.1016/j.asr.2015.10.039. Jimenez, Gonzalo; Jose Pardo, Juan; Minguez, Emilio; Cuervo, Diana (2015): Educational Initiatives to Develop Transversal Skills in the Nuclear Engineering Subjects at Universidad Politecnica de Madrid. In International Journal of Engineering Education 31 (1), pp. 229–237.
Teamwork	Maxon, M. E. 2019 Getting a PhD in a STEM field is a great start to a winning career Journal Article Molecular Biology of the Cell 30 2617-2619 Voitenko, S. Gadasina, L. Sørensen, L. 2018 The need for soft skills for ph.d.'s in software engineering Conference Proceedings Cox, M. F. London, J. S. Ahn, B. Zhu, J. Torres-Ayala, A. T. Frazier, S. Cekic, O. 2011 Attributes of success for engineering Ph.D.s: Perspectives from academia and industry Conference Proceedings Denney, L. B. Sánchez-Peña, M. Main, J. B. 2015 Examining how international experiences promote global competency among engineering graduate students Conference Proceedings Cox, M. F. Zephirin, T. Sambamurthy, N. Ahn, B. London, J. Cekic, O. Torres, A. Zhu, J. B. 2013 Curriculum Vitae Analyses of Engineering Ph.D.s Working in Academia and Industry Journal Article International Journal of Engineering Education 29 1205-1221 Alvarado, A. Price, C. R. 2019 Academic Preparation for Business, Industry, and Government Positions Serial Horta, H. 2018 PhD students' self-perception of skills and career plans while in doctoral programs: are they associated? Journal Article Asia Pacific Education Review 19 211-228 Tavares, O., C. Sin, S. Cardoso and D. Soares 2019 ARE INDUSTRIAL DOCTORATES CAPABLE OF OVERCOMING SKILLS MISMATCH? Book Section Hottenrott, Hanna; Lawson, Cornelia (2017): Flying the nest: how the home department shapes researchers' career paths. In Studies in Higher Education 42 (6), pp. 1091–1109. DOI: 10.1080/03075079.2015.1076782. Abe, Y. Watanabe, S. P. 2012 Some thoughts on implementing US physics doctoral education in Japanese universities Journal Article Asia Pacific Education Review 13 403-415 Woods, K. V. Peek, K. E. Richards-Kortum, R. 2014 Mentoring by Design: Integrating Medical Professional Competencies into Bioengineering and Medical Physics Graduate Training Journal Article Journal of Cancer Education 29 680-688 Jimenez, Gonzalo; Jose Pardo, Juan; Minguez, Emilio; Cuervo, Diana (2015): Educational Initiatives to Develop Transversal Skills in the Nuclear Engineering Subjects at Universidad Politecnica de Madrid. In International Journal of Engineering Education 31 (1), pp. 229–237.
Leadership	Nader, C. 2014 The true value of a PhD in the eyes of industry [Life education] Journal Article IEEE Instrumentation and Measurement Magazine 17 24-25 Voitenko, S. Gadasina, L. Sørensen, L. 2018 The need for soft skills for ph.d.'s in software engineering Conference Proceedings Cox, M. F. London, J. S. Ahn, B. Zhu, J. Torres-Ayala, A. T. Frazier, S. Cekic, O. 2011 Attributes of success for engineering Ph.D.s: Perspectives from academia and industry Conference Proceedings Denney, L. B. Sánchez-Peña, M. Main, J. B. 2015 Examining how international experiences promote global competency among engineering graduate students Conference Proceedings Burylina, G. Sanger, P. A. Ziyatdinova, J. Sultanova, D. 2016 Approaches to entrepreneurship and leadership development at an Engineering University Conference Proceedings

Skill	Sources
	Pisoni, G. Renouard, F. Segovia, J. Rossi, A. Molnar, B. Mutanen, O. P. 2020 Design of small private online courses (SPOCs) for Innovation and entrepreneurship (I&E) Doctoral-level education Book Section Rodrigues, J. C. Freitas, A. Garcia, P. Maia, C. Pierre-Favre, M. Ieee, 2018 Transversal and transferable skills training for engineering PhD/doctoral candidates Book Section Horta, H. 2018 PhD students' self-perception of skills and career plans while in doctoral programs: are they associated? Journal Article Asia Pacific Education Review 19 211-228 Marbouti, F. Lynch, C. D. Asee, 2014 Assessing Doctoral Students' Employability Skills Book Section Hellweg, C. E.; Spitta, L. F.; Kopp, K.; Schmitz, C.; Reitz, G.; Gerzer, R. (2016): Evaluation of an international doctoral educational program in space life sciences: The Helmholtz Space Life Sciences Research School (SpaceLife) in Germany. In Advances in Space Research 57 (1), pp. 378–397. DOI: 10.1016/j.asr.2015.10.039. Cox, Monica Farmer; Zhu, Jiabin; London, Jeremi S.; Ahn, Benjamin; Torres-Ayala, Ana T.; Ramane, Kavitha D. (2012): Recommendations for Promoting Desirable Characteristics in Engineering Ph.D.s: Perspectives from Industry and Academia. In 2014 Asee Annual Conference.
Problem solving	Porter, Anne Marie American Institute of Physics, Statistical Research Center 2018 Physics PhDs Ten Years Later: Duties and Rewards in Government Positions. Results from the PhD Plus 10 Study. Focus On Report Maxon, M. E. 2019 Getting a PhD in a STEM field is a great start to a winning career Journal Article Molecular Biology of the Cell 30 2617-2619 Nader, C. 2014 The true value of a PhD in the eyes of industry [Life education] Journal Article IEEE Instrumentation and Measurement Magazine 17 24-25 Voitenko, S. Gadasina, L. Sørensen, L. 2018 The need for soft skills for ph.d.'s in software engineering Conference Proceedings Watson, J. Lyons, J. S. Asee, 2011 AC 2011-363: A SURVEY OF ESSENTIAL SKILLS FOR PHD ENGINEERS IN INDUSTRY Book Section Cox, M. F. Zephirin, T. Sambamurthy, N. Ahn, B. London, J. Cekic, O. Torres, A. Zhu, J. B. 2013 Curriculum Vitae Analyses of Engineering Ph.D.s Working in Academia and Industry Journal Article International Journal of Engineering Education 29 1205-1221 Sampson, Kaylene Comer, Keith 2011 Engineering Research Teams: The Role of Social Networks in the Formation of Research Skills for Postgraduate Students Journal Article International Journal for the Scholarship of Teaching and Learning 5 Munoz, C. A. Guerra, M. E. Mosey, S. 2020 The potential impact of entrepreneurship education on doctoral students within the non-commercial research environment in Chile Journal Article Studies in Higher Education 45 492-510 Hancock, S. Walsh, E. 2016 Beyond knowledge and skills: rethinking the development of professional identity during the STEM doctorate Journal Article Studies in Higher Education 41 37-50 Hottenrott, Hanna; Lawson, Cornelia (2017): Flying the nest: how the home department shapes researchers' career paths. In Studies in Higher Education 42 (6), pp. 1091–1109. DOI: 10.1080/03075079.2015.1076782. Burt, B. A. 2017 Learning competencies through engineering research group experiences Journal Article Studies in Graduate and Postdoctoral Education 8 48-64
Project management	Maxon, M. E. 2019 Getting a PhD in a STEM field is a great start to a winning career Journal Article Molecular Biology of the Cell 30 2617-2619 Voitenko, S. Gadasina, L. Sørensen, L. 2018 The need for soft skills for ph.d.'s in software engineering Conference Proceedings Rodrigues, J. C. Freitas, A. Garcia, P. Maia, C. Pierre-Favre, M. Ieee, 2018 Transversal and transferable skills training for engineering PhD/doctoral candidates Book Section Didiano, T. J. Wilkinson, L. Turner, J. Franklin, M. Anderson, J. H. Bussmann, M. Reeve, D. Audet, J. 2019 I have a PhD! Now what? A Program to prepare engineering PhDs and post-doctoral fellows for diverse career options Conference Proceedings Marbouti, F. Lynch, C. D. Asee, 2014 Assessing Doctoral Students' Employability Skills Book Section Abe, Y. Watanabe, S. P. 2012 Some thoughts on implementing US physics doctoral education in Japanese universities Journal Article Asia Pacific Education Review 13 403-415

Skill	Sources
	Hellweg, C. E. Gerzer, R. Reitz, G. 2011 A new chapter in doctoral candidate training: The Helmholtz Space Life Sciences Research School (SpaceLife) Journal Article Acta Astronautica 68 1620-1627 Gadasina, L. Voitenko, S. Yurkov, A. 2016 Research of student prospects on developing international PhD programs in software engineering Conference Proceedings Cox, Monica Farmer; Zhu, Jiabin; London, Jeremi S.; Ahn, Benjamin; Torres-Ayala, Ana T.; Ramane, Kavitha D. (2012): Recommendations for Promoting Desirable Characteristics in Engineering Ph.D.s: Perspectives from Industry and Academia. In 2014 Asee Annual Conference. Sinche, Melanie; Layton, Rebekah L.; Brandt, Patrick D.; O'Connell, Anna B.; Hall, Joshua D.; Freeman, Ashalla M. et al. (2017): An evidence-based evaluation of transferrable skills and job satisfaction for science PhDs. In Plos One 12 (9). DOI: 10.1371/journal.pone.0185023.
Business awareness, knowledge and management	Rodrigues, J. C. Freitas, A. Garcia, P. Maia, C. Pierre-Favre, M. Ieee, 2018 Transversal and transferable skills training for engineering PhD/doctoral candidates Book Section Cox, M. F. London, J. S. Ahn, B. Zhu, J. Torres-Ayala, A. T. Frazier, S. Cekic, O. 2011 Attributes of success for engineering Ph.D.s: Perspectives from academia and industry Conference Proceedings Cox, M. F. Zephirin, T. Sambamurthy, N. Ahn, B. London, J. Cekic, O. Torres, A. Zhu, J. B. 2013 Curriculum Vitae Analyses of Engineering Ph.D.s Working in Academia and Industry Journal Article International Journal of Engineering Education 29 1205-1221 Knutas, A. Seffah, A. Sorensen, L. Sozykin, A. Al-Zaghoul, F. Abran, A. 2017 Crossing the Borders and the Cultural Gaps for Educating PhDs in Software Engineering Book Section Pisoni, G. Renouard, F. Segovia, J. Rossi, A. Molnar, B. Mutanen, O. P. 2020 Design of small private online courses (SPOCs) for Innovation and entrepreneurship (I&E) Doctoral-level education Book Section Hottenrott, Hanna; Lawson, Cornelia (2017): Flying the nest: how the home department shapes researchers' career paths. In Studies in Higher Education 42 (6), pp. 1091–1109. DOI: 10.1080/03075079.2015.1076782. Roach, Michael (2017): Encouraging entrepreneurship in university labs: Research activities, research outputs, and early doctorate careers. In Plos One 12 (2). DOI: 10.1371/journal.pone.0170444. Sachani, S. S. 2020 Best of both worlds: A career in technology transfer and business development Journal Article Developmental Biology 459 30-32 Munoz, Cristian A.; Guerra, Mauricio E.; Mosey, Simon (2020): The potential impact of entrepreneurship education on doctoral students within the non-commercial research environment in Chile. In Studies in Higher Education 45 (3), pp. 492–510. DOI: 10.1080/03075079.2019.1597036.
Writing (general and scientific)	Maxon, M. E. 2019 Getting a PhD in a STEM field is a great start to a winning career Journal Article Molecular Biology of the Cell 30 2617-2619 Nader, C. 2014 The true value of a PhD in the eyes of industry [Life education] Journal Article IEEE Instrumentation and Measurement Magazine 17 24-25 Voitenko, S. Gadasina, L. Sørensen, L. 2018 The need for soft skills for ph.d.'s in software engineering Conference Proceedings Knutas, A. Seffah, A. Sorensen, L. Sozykin, A. Al-Zaghoul, F. Abran, A. 2017 Crossing the Borders and the Cultural Gaps for Educating PhDs in Software Engineering Book Section Tavares, O., C. Sin, S. Cardoso and D. Soares 2019 ARE INDUSTRIAL DOCTORATES CAPABLE OF OVERCOMING SKILLS MISMATCH? Book Section Kim, Jeongeun; Ott, Molly; Dippold, Lindsey (2020): University and Department Influences on Scientists' Occupational Outcomes. In Research in Higher Education 61 (2), pp. 197–228. DOI: 10.1007/s11162-019-09584-6. Hellweg, C. E.; Spitta, L. F.; Kopp, K.; Schmitz, C.; Reitz, G.; Gerzer, R. (2016): Evaluation of an international doctoral educational program in space life sciences: The Helmholtz Space Life Sciences Research School (SpaceLife) in Germany. In Advances in Space Research 57 (1), pp. 378–397. DOI: 10.1016/j.asr.2015.10.039. Virkki-Hatakka: Enhancing Doctoral Studies of Part-Time Students - The interdisciplinary Researc Group for the Researchers working in companies. Cox, Monica Farmer; Zhu, Jiabin; London, Jeremi S.; Ahn, Benjamin; Torres-Ayala, Ana T.; Ramane, Kavitha D. (2012): Recommendations for Promoting Desirable

Skill	Sources
	Characteristics in Engineering Ph.D.s: Perspectives from Industry and Academia. In 2014 Asee Annual Conference.
Teaching	Cox, M. F. London, J. S. Ahn, B. Zhu, J. Torres-Ayala, A. T. Frazier, S. Cekic, O. 2011 Attributes of success for engineering Ph.D.s: Perspectives from academia and industry Conference Proceedings Nader, C. 2014 The true value of a PhD in the eyes of industry [Life education] Journal Article IEEE Instrumentation and Measurement Magazine 17 24-25 Cox, M. F. Zephirin, T. Sambamurthy, N. Ahn, B. London, J. Cekic, O. Torres, A. Zhu, J. B. 2013 Curriculum Vitae Analyses of Engineering Ph.D.s Working in Academia and Industry Journal Article International Journal of Engineering Education 29 1205-1221 Sampson, Kaylene Comer, Keith 2011 Engineering Research Teams: The Role of Social Networks in the Formation of Research Skills for Postgraduate Students Journal Article International Journal for the Scholarship of Teaching and Learning 5 Abe, Y. Watanabe, S. P. 2012 Some thoughts on implementing US physics doctoral education in Japanese universities Journal Article Asia Pacific Education Review 13 403-415 Porter, Anne Marie American Institute of Physics, Statistical Research Center 2018 Physics PhDs Ten Years Later: Duties and Rewards in Academic Positions. Results from the PhD Plus 10 Study. Cox, Monica Farmer; Zhu, Jiabin; London, Jeremi S.; Ahn, Benjamin; Torres-Ayala, Ana T.; Ramane, Kavitha D. (2012): Recommendations for Promoting Desirable Characteristics in Engineering Ph.D.s: Perspectives from Industry and Academia. In 2014 Asee Annual Conference. Prevost, L. B. Vergara, C. E. Urban-Lurain, M. Campa, H., III 2018 Evaluation of a High-Engagement Teaching Program for STEM Graduate Students: Outcomes of the Future Academic Scholars in Teaching (FAST) Fellowship Program Journal Article Innovative Higher Education 43 41-55
Presentations	Maxon, M. E. 2019 Getting a PhD in a STEM field is a great start to a winning career Journal Article Molecular Biology of the Cell 30 2617-2619 Knutas, A. Seffah, A. Sorensen, L. Sozykin, A. Al-Zaghoul, F. Abran, A. 2017 Crossing the Borders and the Cultural Gaps for Educating PhDs in Software Engineering Book Section Dolgopolovas, V. Dagienė, V. Jevsikova, T. 2020 Student-Centered Graduate STEM Education Integrated by Computing: An Insight into the Experiences and Expectations of Doctoral Students Serial Hellweg, C. E. Gerzer, R. Reitz, G. 2011 A new chapter in doctoral candidate training: The Helmholtz Space Life Sciences Research School (SpaceLife) Journal Article Acta Astronautica 68 1620-1627 Kim, Jeongeun; Ott, Molly; Dippold, Lindsey (2020): University and Department Influences on Scientists' Occupational Outcomes. In Research in Higher Education 61 (2), pp. 197–228. DOI: 10.1007/s11162-019-09584-6. Hellweg, C. E.; Spitta, L. F.; Kopp, K.; Schmitz, C.; Reitz, G.; Gerzer, R. (2016): Evaluation of an international doctoral educational program in space life sciences: The Helmholtz Space Life Sciences Research School (SpaceLife) in Germany. In Advances in Space Research 57 (1), pp. 378–397. DOI: 10.1016/j.asr.2015.10.039. Burt, B. A. 2017 Learning competencies through engineering research group experiences Journal Article Studies in Graduate and Postdoctoral Education 8 48-64
Cultural sensitivity & reflexivity	Voitenko, S. Gadasina, L. Sørensen, L. 2018 The need for soft skills for ph.d.'s in software engineering Conference Proceedings Knutas, A. Seffah, A. Sorensen, L. Sozykin, A. Al-Zaghoul, F. Abran, A. 2017 Crossing the Borders and the Cultural Gaps for Educating PhDs in Software Engineering Book Section Hancock, S. Walsh, E. 2016 Beyond knowledge and skills: rethinking the development of professional identity during the STEM doctorate Journal Article Studies in Higher Education 41 37-50 Ortega, Suzanne T. Kent, Julia D. 2018 What Is a PhD? Reverse-Engineering Our Degree Programs in the Age of Evidence-Based Change Journal Article Change: The Magazine of Higher Learning 50 30-36 Woods, K. V. Peek, K. E. Richards-Kortum, R. 2014 Mentoring by Design: Integrating Medical Professional Competencies into Bioengineering and Medical Physics Graduate Training Journal Article Journal of Cancer Education 29 680-688

Skill	Sources
Specialised knowledge	Maxon, M. E. 2019 Getting a PhD in a STEM field is a great start to a winning career Journal Article Molecular Biology of the Cell 30 2617-2619 Nader, C. 2014 The true value of a PhD in the eyes of industry [Life education] Journal Article IEEE Instrumentation and Measurement Magazine 17 24-25 Denney, L. B. Sánchez-Peña, M. Main, J. B. 2015 Examining how international experiences promote global competency among engineering graduate students Conference Proceedings Cox, M. F. Zephirin, T. Sambamurthy, N. Ahn, B. London, J. Cekic, O. Torres, A. Zhu, J. B. 2013 Curriculum Vitae Analyses of Engineering Ph.D.s Working in Academia and Industry Journal Article International Journal of Engineering Education 29 1205-1221 Rodrigues, J. C. Freitas, A. Garcia, P. Maia, C. Pierre-Favre, M. Ieee, 2018 Transversal and transferable skills training for engineering PhD/doctoral candidates Book Section
Adaptability	Voitenko, S. Gadasina, L. Sørensen, L. 2018 The need for soft skills for ph.d.'s in software engineering Conference Proceedings Cox, M. F. London, J. S. Ahn, B. Zhu, J. Torres-Ayala, A. T. Frazier, S. Cekic, O. 2011 Attributes of success for engineering Ph.D.s: Perspectives from academia and industry Conference Proceedings Dolgopolovas, V. Dagienė, V. Jevsikova, T. 2020 Student-Centered Graduate STEM Education Integrated by Computing: An Insight into the Experiences and Expectations of Doctoral Students Serial Horta, H. 2018 PhD students' self-perception of skills and career plans while in doctoral programs: are they associated? Journal Article Asia Pacific Education Review 19 211-228
Analytical skills	Voitenko, S. Gadasina, L. Sørensen, L. 2018 The need for soft skills for ph.d.'s in software engineering Conference Proceedings Cox, M. F. London, J. S. Ahn, B. Zhu, J. Torres-Ayala, A. T. Frazier, S. Cekic, O. 2011 Attributes of success for engineering Ph.D.s: Perspectives from academia and industry Conference Proceedings Denney, L. B. Sánchez-Peña, M. Main, J. B. 2015 Examining how international experiences promote global competency among engineering graduate students Conference Proceedings Cox, M. F. Zephirin, T. Sambamurthy, N. Ahn, B. London, J. Cekic, O. Torres, A. Zhu, J. B. 2013 Curriculum Vitae Analyses of Engineering Ph.D.s Working in Academia and Industry Journal Article International Journal of Engineering Education 29 1205-1221
Collaborative working habits	Rodrigues, J. C. Freitas, A. Garcia, P. Maia, C. Pierre-Favre, M. Ieee, 2018 Transversal and transferable skills training for engineering PhD/doctoral candidates Book Section Hancock, S. Walsh, E. 2016 Beyond knowledge and skills: rethinking the development of professional identity during the STEM doctorate Journal Article Studies in Higher Education 41 37-50 Hottenrott, Hanna; Lawson, Cornelia (2017): Flying the nest: how the home department shapes researchers' career paths. In Studies in Higher Education 42 (6), pp. 1091–1109. DOI: 10.1080/03075079.2015.1076782. Porter, Anne Marie American Institute of Physics, Statistical Research Center 2018 Physics PhDs Ten Years Later: Duties and Rewards in Academic Positions. Results from the PhD Plus 10 Study.
Creativity	Voitenko, S. Gadasina, L. Sørensen, L. 2018 The need for soft skills for ph.d.'s in software engineering Conference Proceedings Cox, M. F. London, J. S. Ahn, B. Zhu, J. Torres-Ayala, A. T. Frazier, S. Cekic, O. 2011 Attributes of success for engineering Ph.D.s: Perspectives from academia and industry Conference Proceedings Dolgopolovas, V. Dagienė, V. Jevsikova, T. 2020 Student-Centered Graduate STEM Education Integrated by Computing: An Insight into the Experiences and Expectations of Doctoral Students Serial Hancock, S. 2019 A future in the knowledge economy? Analysing the career strategies of doctoral scientists through the principles of game theory Journal Article Higher Education 78 33-49
Negotiation	Voitenko, S. Gadasina, L. Sørensen, L. 2018 The need for soft skills for ph.d.'s in software engineering Conference Proceedings Tavares, O., C. Sin, S. Cardoso and D. Soares 2019 ARE INDUSTRIAL DOCTORATES CAPABLE OF OVERCOMING SKILLS MISMATCH? Book Section

Skill	Sources
	Hancock, S. Walsh, E. 2016 Beyond knowledge and skills: rethinking the development of professional identity during the STEM doctorate Journal Article Studies in Higher Education 41 37-50 Gadasina, L. Voitenko, S. Yurkov, A. 2016 Research of student prospects on developing international PhD programs in software engineering Conference Proceedings
Specialised knowledge	Maxon, M. E. 2019 Getting a PhD in a STEM field is a great start to a winning career Journal Article Molecular Biology of the Cell 30 2617-2619 Nader, C. 2014 The true value of a PhD in the eyes of industry [Life education] Journal Article IEEE Instrumentation and Measurement Magazine 17 24-25 Denney, L. B. Sánchez-Peña, M. Main, J. B. 2015 Examining how international experiences promote global competency among engineering graduate students Conference Proceedings Rodrigues, J. C. Freitas, A. Garcia, P. Maia, C. Pierre-Favre, M. Ieee, 2018 Transversal and transferable skills training for engineering PhD/doctoral candidates Book Section
Time management (and working to deadlines)	Maxon, M. E. 2019 Getting a PhD in a STEM field is a great start to a winning career Journal Article Molecular Biology of the Cell 30 2617-2619 Sampson, Kaylene Comer, Keith 2011 Engineering Research Teams: The Role of Social Networks in the Formation of Research Skills for Postgraduate Students Journal Article International Journal for the Scholarship of Teaching and Learning 5 Horta, H. 2018 PhD students' self-perception of skills and career plans while in doctoral programs: are they associated? Journal Article Asia Pacific Education Review 19 211-228 Sinche, Melanie; Layton, Rebekah L.; Brandt, Patrick D.; O'Connell, Anna B.; Hall, Joshua D.; Freeman, Ashalla M. et al. (2017): An evidence-based evaluation of transferrable skills and job satisfaction for science PhDs. In Plos One 12 (9). DOI: 10.1371/journal.pone.0185023.
Answering multidisciplinary research questions	Maxon, M. E. 2019 Getting a PhD in a STEM field is a great start to a winning career Journal Article Molecular Biology of the Cell 30 2617-2619 Cox, M. F. London, J. S. Ahn, B. Zhu, J. Torres-Ayala, A. T. Frazier, S. Cekic, O. 2011 Attributes of success for engineering Ph.D.s: Perspectives from academia and industry Conference Proceedings Naukkarinen, J. K. (2016): Doctoral education in engineering: training for science or industry? 44th SEFI Conference. Finland, checked on 2/7/2021.
General management skills	Germain-Alamartine, E. Ahoba-Sam, R. Moghadam-Saman, S. Evers, G. Doctoral graduates' transition to industry: networks as a mechanism? Cases from Norway, Sweden and the UK Journal Article Studies in Higher Education 16 Dolgopolovas, V. Dagienė, V. Jevsikova, T. 2020 Student-Centered Graduate STEM Education Integrated by Computing: An Insight into the Experiences and Expectations of Doctoral Students Serial Horta, H. 2018 PhD students' self-perception of skills and career plans while in doctoral programs: are they associated? Journal Article Asia Pacific Education Review 19 211-228
Identify and systematically develop novel solutions for complex problems using advanced theoretical knowledge	Porter, Anne Marie American Institute of Physics, Statistical Research Center 2018 Physics PhDs Ten Years Later: Duties and Rewards in Government Positions. Results from the PhD Plus 10 Study. Focus On Report Maxon, M. E. 2019 Getting a PhD in a STEM field is a great start to a winning career Journal Article Molecular Biology of the Cell 30 2617-2619 Nader, C. 2014 The true value of a PhD in the eyes of industry [Life education] Journal Article IEEE Instrumentation and Measurement Magazine 17 24-25
Integration of innovation solutions with appropriate recognition of customer requirements	Pisoni, G. Renouard, F. Segovia, J. Rossi, A. Molnar, B. Mutanen, O. P. 2020 Design of small private online courses (SPOCs) for Innovation and entrepreneurship (I&E) Doctoral-level education Book Section Rodrigues, J. C. Freitas, A. Garcia, P. Maia, C. Pierre-Favre, M. Ieee, 2018 Transversal and transferable skills training for engineering PhD/doctoral candidates Book Section Germain-Alamartine, E. Moghadam-Saman, S. 2020 Aligning doctoral education with local industrial employers' needs: a comparative case study Journal Article European Planning Studies 28 234-254
Accountability	Voitenko, S. Gadasina, L. Sørensen, L. 2018 The need for soft skills for ph.d.'s in software engineering Conference Proceedings Woods, K. V. Peek, K. E. Richards-Kortum, R. 2014 Mentoring by Design: Integrating Medical Professional Competencies into Bioengineering and Medical Physics Graduate Training Journal Article Journal of Cancer Education 29 680-688

Skill	Sources
Argumentation	Sampson, Kaylene Comer, Keith 2011 Engineering Research Teams: The Role of Social Networks in the Formation of Research Skills for Postgraduate Students Journal Article International Journal for the Scholarship of Teaching and Learning 5 Gonsalves, A. J. 2018 Exploring how gender figures the identity trajectories of two doctoral students in observational astrophysics Journal Article Physical Review Physics Education Research 14
Critical reasoning	Voitenko, S. Gadasina, L. Sørensen, L. 2018 The need for soft skills for ph.d.'s in software engineering Conference Proceedings Sampson, Kaylene Comer, Keith 2011 Engineering Research Teams: The Role of Social Networks in the Formation of Research Skills for Postgraduate Students Journal Article International Journal for the Scholarship of Teaching and Learning 5
Derive realizable solutions not seen by others	Nader, C. 2014 The true value of a PhD in the eyes of industry [Life education] Journal Article IEEE Instrumentation and Measurement Magazine 17 24-25 Rodrigues, J. C. Freitas, A. Garcia, P. Maia, C. Pierre-Favre, M. Ieee, 2018 Transversal and transferable skills training for engineering PhD/doctoral candidates Book Section
Exceed the existing technical and scientific knowledge of the industry	Rodrigues, J. C. Freitas, A. Garcia, P. Maia, C. Pierre-Favre, M. Ieee, 2018 Transversal and transferable skills training for engineering PhD/doctoral candidates Book Section Lattanzio, Susan; Sajdakova, Jana; Burke, Richard; Parry, Glenn; Newnes, Linda (2020): Towards a Practical Approach for TE Education: A Pilot Study at the University of Bath. In Transdisciplinary Engineering for Complex Socio-Technical Systems - Real-Life Applications 12, pp. 73–81. DOI: 10.3233/ATDE200063.
Flexibility	Voitenko, S. Gadasina, L. Sørensen, L. 2018 The need for soft skills for ph.d.'s in software engineering Conference Proceedings Tavares, O., C. Sin, S. Cardoso and . Soares 2019 ARE INDUSTRIAL DOCTORATES CAPABLE OF OVERCOMING SKILLS MISMATCH? Book Section
Independent working	Watson, J. Lyons, J. S. Asee, 2011 AC 2011-363: A SURVEY OF ESSENTIAL SKILLS FOR PHD ENGINEERS IN INDUSTRY Book Section Barnard, R. A. Shultz, G. V. 2020 Most important is that they figure out how to solve the problem: how do advisors conceptualize and develop research autonomy in chemistry doctoral students? Journal Article Higher Education 79 981-999
Obtaining funding	Cox, M. F. London, J. S. Ahn, B. Zhu, J. Torres-Ayala, A. T. Frazier, S. Cekic, O. 2011 Attributes of success for engineering Ph.D.s: Perspectives from academia and industry Conference Proceedings Cox, M. F. Zephirin, T. Sambamurthy, N. Ahn, B. London, J. Cekic, O. Torres, A. Zhu, J. B. 2013 Curriculum Vitae Analyses of Engineering Ph.D.s Working in Academia and Industry Journal Article International Journal of Engineering Education 29 1205-1221
People management	Rodrigues, J. C. Freitas, A. Garcia, P. Maia, C. Pierre-Favre, M. Ieee, 2018 Transversal and transferable skills training for engineering PhD/doctoral candidates Book Section Cox, Monica Farmer; Zhu, Jiabin; London, Jeremi S.; Ahn, Benjamin; Torres-Ayala, Ana T.; Ramane, Kavitha D. (2012): Recommendations for Promoting Desirable Characteristics in Engineering Ph.D.s: Perspectives from Industry and Academia. In 2014 Asee Annual Conference.
Providing/receiving constructive criticism	Maxon, M. E. 2019 Getting a PhD in a STEM field is a great start to a winning career Journal Article Molecular Biology of the Cell 30 2617-2619 Burt, B. A. 2017 Learning competencies through engineering research group experiences Journal Article Studies in Graduate and Postdoctoral Education 8 48-64
Reasoning	Nader, C. 2014 The true value of a PhD in the eyes of industry [Life education] Journal Article IEEE Instrumentation and Measurement Magazine 17 24-25 Sampson, Kaylene Comer, Keith 2011 Engineering Research Teams: The Role of Social Networks in the Formation of Research Skills for Postgraduate Students Journal Article International Journal for the Scholarship of Teaching and Learning 5
Research methods	Maxon, M. E. 2019 Getting a PhD in a STEM field is a great start to a winning career Journal Article Molecular Biology of the Cell 30 2617-2619 Nader, C. 2014 The true value of a PhD in the eyes of industry [Life education] Journal Article IEEE Instrumentation and Measurement Magazine 17 24-25

Skill	Sources
Strategies for finding and processing new information	Nader, C. 2014 The true value of a PhD in the eyes of industry [Life education] Journal Article IEEE Instrumentation and Measurement Magazine 17 24-25 Sampson, Kaylene Comer, Keith 2011 Engineering Research Teams: The Role of Social Networks in the Formation of Research Skills for Postgraduate Students Journal Article International Journal for the Scholarship of Teaching and Learning 5
Conducting effective meetings	Maxon, M. E. 2019 Getting a PhD in a STEM field is a great start to a winning career Journal Article Molecular Biology of the Cell 30 2617-2619
Curiosity	Nader, C. 2014 The true value of a PhD in the eyes of industry [Life education] Journal Article IEEE Instrumentation and Measurement Magazine 17 24-25
Dedication	Horta, H. 2018 PhD students' self-perception of skills and career plans while in doctoral programs: are they associated? Journal Article Asia Pacific Education Review 19 211-228
Determination	Horta, H. 2018 PhD students' self-perception of skills and career plans while in doctoral programs: are they associated? Journal Article Asia Pacific Education Review 19 211-228
Identify systematic and chaotic errors, gain trust in unbiased work	Nader, C. 2014 The true value of a PhD in the eyes of industry [Life education] Journal Article IEEE Instrumentation and Measurement Magazine 17 24-25
Information sharing	Nader, C. 2014 The true value of a PhD in the eyes of industry [Life education] Journal Article IEEE Instrumentation and Measurement Magazine 17 24-25
Information, media and ICT literacy	Voitenko, S. Gadasina, L. Sørensen, L. 2018 The need for soft skills for ph.d.'s in software engineering Conference Proceedings
Initiative	Voitenko, S. Gadasina, L. Sørensen, L. 2018 The need for soft skills for ph.d.'s in software engineering Conference Proceedings
Investigating current systems	Nader, C. 2014 The true value of a PhD in the eyes of industry [Life education] Journal Article IEEE Instrumentation and Measurement Magazine 17 24-25
Mutuality (through co-publication)	Sampson, Kaylene Comer, Keith 2011 Engineering Research Teams: The Role of Social Networks in the Formation of Research Skills for Postgraduate Students Journal Article International Journal for the Scholarship of Teaching and Learning 5
Perseverance	Horta, H. 2018 PhD students' self-perception of skills and career plans while in doctoral programs: are they associated? Journal Article Asia Pacific Education Review 19 211-228
Programming (designing, writing, maintaining, and testing codes)	Dolgopolovas, V. Dagienė, V. Jevsikova, T. 2020 Student-Centered Graduate STEM Education Integrated by Computing: An Insight into the Experiences and Expectations of Doctoral Students Serial
Publications	Cox, M. F. London, J. S. Ahn, B. Zhu, J. Torres-Ayala, A. T. Frazier, S. Cekic, O. 2011 Attributes of success for engineering Ph.D.s: Perspectives from academia and industry Conference Proceedings
Resilience	Horta, H. 2018 PhD students' self-perception of skills and career plans while in doctoral programs: are they associated? Journal Article Asia Pacific Education Review 19 211-228
Responsibility	Voitenko, S. Gadasina, L. Sørensen, L. 2018 The need for soft skills for ph.d.'s in software engineering Conference Proceedings
Self-criticism	Nader, C. 2014 The true value of a PhD in the eyes of industry [Life education] Journal Article IEEE Instrumentation and Measurement Magazine 17 24-25
Writing memos	Maxon, M. E. 2019 Getting a PhD in a STEM field is a great start to a winning career Journal Article Molecular Biology of the Cell 30 2617-2619
Designing experiments	Hottenrott, Hanna; Lawson, Cornelia (2017): Flying the nest: how the home department shapes researchers' career paths. In Studies in Higher Education 42 (6), pp. 1091–1109. DOI: 10.1080/03075079.2015.1076782.
Ethics (e.g. bioethics)	Woods, K. V. Peek, K. E. Richards-Kortum, R. 2014 Mentoring by Design: Integrating Medical Professional Competencies into Bioengineering and Medical Physics Graduate Training Journal Article Journal of Cancer Education 29 680-688