The role of pre-formation intangible assets in the endowment of science-based university spin-offs

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Abstract: Science-based university spin-offs face considerable technology and market uncertainty over extended periods of time, increasing the challenges of commercialisation. Scientist-entrepreneurs can play formative roles in commercialising lab-based scientific inventions through the formation of well-endowed university spin-offs. Through case study analysis of three science-based university spin-offs within a biotechnology innovation ecosystem, we unpack the impact of *pre-formation* intangible assets of academic scientists (research excellence, patenting, and international networks) and their entrepreneurial capabilities on spin-off performance. We find evidence that the pre-formation entrepreneurial capabilities of academic scientists can endow science-based university spin-offs by leveraging the scientists' pre-formation intangible assets. A theory-driven model depicting the role of pre-formation intangible assets and entrepreneurial capabilities in endowing science-based university spin-offs is developed. Recommendations are provided for scholars, practitioners, and policymakers to more effectively commercialise high potential inventions in the university lab through the development and deployment of pre-formation intangible assets and entrepreneurial capabilities.

Keywords: intangible assets; entrepreneurial capabilities; university spin-offs; scientist-entrepreneurs; academic scientists; dynamic capabilities; firm performance; pre-formation; biotechnology; science-based ventures; international networks; innovation policy; academic entrepreneurship; science innovation; innovation ecosystems.

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1 Introduction

Science-based university spin-offs are increasingly being recognised for their role in addressing significant challenges facing society. For example, emerging evidence suggests that science-based university spin-offs were at the forefront in the development of COVID-19 therapeutics and vaccines (Park et al., 2022; Kisby et al., 2021). Such evidence of the global societal impact of science-based university spin-offs is leading to further examination of the assets and capabilities of academic scientist co-founders, enabling the emergence of these ventures.

Academic scientists can play a critical role in the formation of scalable university spin-offs. However, the commercialisation of scientific inventions often involves significant challenges, such as prohibitive costs and long timelines to bring products to market, for example, as in case of novel drug development (Pisano, 2010). Compared to a software start-up, a biotechnology venture can spend over one hundred times the money and often take ten times as long to commercialise its invention (Maine and Seegopaul, 2016). Despite these challenges, governments are increasingly interested in enabling the formation and growth of science-based university spin-offs, due to their significant potential to generate economic and societal value. Entrepreneurship scholars agree that the pre-formation stage of these ventures is understudied and have called for further research examining this formative period (Druilhe and Garnsey, 2004; Phan, 2004; Rasmussen et al., 2011). Recent research on science-based university spin-offs demonstrates how the development and deployment of entrepreneurial capabilities in the pre-formation stage can better prepare science-based university spin-offs to manage the significant scientific and market uncertainties inherent in the science commercialisation process (Thomas et al., 2020). The pre-formation stage is also when valuable firm-specific intangible assets such as the knowledge embodied in patents and publications are initially developed. The individual-level intangible assets of academic co-founders and the entrepreneurial capabilities developed and deployed during this pre-formation stage in the research lab are closely linked to the sensing and shaping and seizing dynamic capabilities of the science-based university spin-offs post-formation (Thomas et al., 2020).

While tangible assets such as venture capital funding can aid the growth of a science-based firm, intangible assets are receiving increasing attention in the management literature (Heirman and Clarysse, 2007; Awano et al., 2010; Kramer et al., 2011; Crema and Nosella, 2014; Grimaldi et al., 2017). Part of the reason for this interest is the realisation by economists that intangible assets are critical inputs into the innovation process – in the USA, investment in intangible assets roughly equals investment in tangible assets – but the link between intangible asset investment and commercialisation is not well understood (Aizcorbe et al., 2009).

Though the importance of entrepreneurial capabilities and intangible assets are increasingly being recognised, the interplay between entrepreneurial capabilities and intangible assets and how this interplay can lead to enhanced firm performance remains understudied. This is particularly relevant in the context of science-based ventures as few of these ventures survive long periods of time and fewer still achieve significant growth in annual revenues or employees. More specifically, we seek to examine how entrepreneurial capabilities and pre-formation intangible assets impact the performance of science-based university spin-offs.

To answer this question, we conduct a comparative case analysis of three science-based university spin-offs emerging from the same biotechnology innovation ecosystem. While all three firms exhibit higher levels of uncertainty as compared to non-science-based ventures, they also differ significantly in the levels of uncertainty each of them faces, thus serving as natural comparative test cases that elucidate the relationships between intangible assets and entrepreneurial capabilities and their impact on firm formation, survival, and performance.

Process-oriented case studies which account for context, temporality, and sequencing are particularly well suited to the phenomenon of science-based university spin-off emergence and the growth that often occurs over a period of several decades (Rasmussen et al., 2011; Schilke et al., 2018). Furthermore, this multiple case approach allows for the identification of patterns, which can be achieved by selecting categories and looking for interfirm similarities or differences (Eisenhardt, 1989). The patterns arising from our firm-level case studies of the biotechnology innovation ecosystem will allow for a better understanding of the role of pre-formation intangible assets and entrepreneurial capabilities in firm performance.

We elucidate how pre-formation intangible assets and entrepreneurial capabilities play a critical role in the formation, survival, and success of science-based university spin-offs. In particular, we observe that knowledge-based pre-formation intangible assets aid future firm success and are *mobilised* through the entrepreneurial capabilities of technology-market matching, claiming and protecting the invention, attracting and mentoring the founding team, and strategic timing of firm formation. Interpreting these observations in light of existing theory, a model is developed and presented that depicts the interplay between pre-formation intangible assets and entrepreneurial capabilities, which leads to enhanced firm performance. We conclude by offering suggestions to scholars, practitioners, and policymakers on how to develop and leverage pre-formation intangible assets and entrepreneurial capabilities to better enable the formation, survival, and performance of university spin-offs for societal impact.

2 Literature review

While it is increasingly recognised that science-based ventures can have significant societal impact, not much is known about the manner in which academic scientist co-founders can leverage their pre-formation intangible assets to drive post-formation firm survival and performance. Science-based ventures, of which biotechnology and life sciences ventures are a subset, are often spun out of universities because their core technologies are predicated on years of lab-based research. Hence, science-based university spin-offs offer a valuable context to explore the interactions between pre-formation intangible assets, entrepreneurial capabilities, and firm performance.

2.1 Intangible assets

Over the last two decades, there has been increasing interest in studying the impact of intangible assets on value creation (Kaufmann and Schneider, 2004; Dean and Kretschmer, 2007; Crema and Nosella, 2014). Research on intangible assets has its roots dating back to Polanyi's (1958) work on tacit knowledge; however, Nonaka and Takeuchi's (1995) seminal contribution on firms and knowledge creation was the catalyst that spurred broad research interest in this field. While the specific definition of intangible assets has been debated in prior literature, scholars generally agree that these assets do not take a physical or monetary form, such as machinery or cash, but that they are nevertheless important contributors to developing competitive advantage (Bontis et al., 1999; Lev, 2003; Teece, 2007; Martín-de-Castro et al., 2011).

The resource-based view of the firm (Penrose, 1959; Wernerfelt, 1984) is a centrepiece in the strategy literature that has spurred numerous streams of related empirical and conceptual research, but the specific role intangible assets play in driving innovation performance, particularly for science-based ventures, which are characterised by high technology and market uncertainty, is much less understood. Managers often have a much more difficult time identifying and assessing the intangible assets their firms possess, compared to tangible assets such as property and financial resources, and thus are poorly equipped to translate those intangible assets into improved innovation outcomes (Aizcorbe et al., 2009). While all managers face a challenge identifying and leveraging intangible assets, it can be an even more complex task for academic scientists whose training and expertise typically does not include technology management skills. Given that the body of literature surrounding intangible assets has not yet reached the same level of maturity as the resource-based view of the firm, methods to empirically study the role of intangible assets in value creation are still being developed, and consensus has not yet been reached on how to quantify and assess the stock of intangible assets within a firm (Kaufmann and Schneider, 2004; Osinski et al., 2017). Some methods that have been used in prior research to evaluate the level of intangible assets in a firm have been categorised by Van Criekingen et al. (2021), Crema and Nosella (2014) and Sveiby (2010) and include a scorecard method (Edvinsson and Malone, 1997), attributing financial value to specific intangible assets (Andriessen, 2005), and an aggregate method for quantifying the monetary value of a basket of intangible assets (Aho et al., 2011).

Given that the methods used to identify and assess intangible assets are still in their nascency, there is much opportunity to conduct empirical work in this field, and the contexts that are chosen for empirical research will likely lead to a broad array of novel findings related to the role these assets play in driving firm performance outcomes in specific industries. Intangible assets are particularly valuable to science-based university spin-offs as they require substantial financing to weather the prolonged uncertainty and timelines associated with the commercialisation of their technologies (Maine and Thomas, 2017). To attract this financing without a market-ready product – and sometimes before a significant market is even created – they must rely on knowledge-based intangible assets such as patents and research publications to signal scientific quality and research progress leading to potential value capture. Thus, the focus of this paper is to understand the relationship between pre-formation intangible assets, entrepreneurial capabilities, and performance of science-based university spin-offs.

2.2 Uncertainty and the intangible assets of academic scientist-entrepreneurs

Science-based businesses typically operate in environments with high levels of uncertainty (Pisano, 2010). This uncertainty can be further sub-divided into technology and market uncertainty (Maine and Garnsey, 2006). Technology uncertainty refers to the significant challenges in the development, integration, and process scale-up of the advances in multiple disciplines such as in the case of nanobiotechnology (Maine and Thomas, 2017) or advanced materials (Maine and Seegopaul, 2016), which then form the basis of the products and services developed by science-based businesses. The challenge for the science-based business in such complex settings is that "the time horizons to resolve fundamental uncertainty can be quite long" (Pisano, 2010) and during that extended period of time significant capital must be invested in hopes of resolving technology uncertainty (Maine and Seegopaul, 2016).

The market uncertainty faced by a science-based business can also be significantly different from other ventures. Pisano (2010) notes that science-based businesses can have multiple years without product revenues and there may not be a guarantee to appropriate any returns even if technology uncertainty is resolved. For example, the standard of care for a disease indication could change or the production economics could prove unviable. For many biotechnology start-ups, and particularly those working with platform technologies, it is not only important to signal the value of the technology through patents, publications, and manufacturing scale-up, it is also critical to "develop both the platform and a product that demonstrates the capabilities of the platform" (Maine and Thomas, 2017). Given multiple potential market applications for the technologies developed by science-based businesses, a careful assessment of "the lead candidate, target disease indications and the breadth of their technology portfolio" can become crucial for biotechnology start-ups to meet investor expectations and timelines (Maine and Thomas, 2017; Pisano, 2010).

The concept of uncertainty has been extensively studied including by scholars using relative scales of uncertainty to rank order firms or projects (Brown and Utterback, 1985; Hitt et al., 1982; Alvarez and Barney, 2005; Maine et al., 2015). For biotechnology companies, this uncertainty and the associated long timeline are highest for therapeutics (DiMasi et al., 2010) and somewhat reduced for diagnostics and instrumentation, with reagent suppliers the least uncertain and with the shortest timeline. Signalling to investors with intangible assets becomes even more important as uncertainty and commercialisation timelines increase. For example, Hsu and Ziedonis (2008) note that patents can be used as signalling mechanisms to attract venture capital financing and external partnerships. Such financing is critical during the long R&D and pre-commercialisation period that is often seen in the biotechnology sector (Baum and Silverman, 2004; Maine and Thomas, 2017). While patents have been acknowledged as indicators of inventive activity, there is increasing recognition that scientific inventors also hold significant tacit knowledge and "know more than is written in patent applications" (Maurseth and Svensson, 2020). Such tacit knowledge plays an important role in science commercialisation.

Publishing in elite journals can be viewed as a mechanism to signal credibility and research excellence (Maine and Thomas, 2017). This publishing activity by inventors, founders and later the firms themselves is particularly relevant in the context of biotechnology spin-offs as the techniques and tools they seek to commercialise often have a significant element of newness and thus may be incompletely codified and have higher levels of tacit knowledge particularly in the early stages of technology development. This tacit knowledge could include troubleshooting (Barley and Bechky, 1994) or the learning generated through related failed experiments (Agrawal, 2006). Scholars also note that while publications often seek to disseminate successful experiments (Agrawal, 2006), economically valuable findings without publication relevance often remain tacit (Karnani, 2013). As Barley and Bechky (1994) eloquently note "… (although) methods sections of scientific papers might imply that one could follow procedures as if they were recipes, lab workers were acutely aware that routine encounters with the material world were unpredictable … [and] … had an uncanny capacity for recalcitrance." Published papers may thus be viewed as the tip of the iceberg with much relevant and related tacit knowledge embedded in inventors' minds and not easily accessible.

The papers also serve another valuable function. As Hicks (1995) notes, publicising scientific results through papers and conference presentations act as signals to attract scientific and commercialisation collaborators, with these elite journal papers becoming the currency through which scientists convey research excellence which then facilitates the initiation and strengthening of scientific collaboration and commercialisation networks.

Another key intangible asset that academic co-founders of science-based university spin-offs often possess is access to *external and international networks*. Prior research has shown that the external networks are positively correlated to firm-level innovation performance (Christensen et al., 2005; Laursen and Salter, 2014). While founders' prior start-up experience, connections to VC investors (Shane and Stuart, 2002), or USOs' links to parent universities (Bolzani et al., 2021) have been found to impact firm performance, not much is known about the impact of the *pre-formation* collaboration networks of academic co-founders on post-formation venture performance. This is particularly relevant in the context of science-based university spin-offs facing high levels of technology and market uncertainty as firms operating in conditions of high uncertainty have limited resources and must rely on external sources of knowledge and capabilities (Niosi, 2003; Baum and Silverman, 2004). Beyond capabilities and knowledge to co-develop novel products and services, academic scientists' international networks can be mobilised by the nascent science-based venture in product beta-testing and to facilitate sales. The influence of such pre-formation intangible assets on firm survival and performance of these biotechnology firms is thus a critical area of study for scholars, academic scientists, university leadership, and policymakers who wish to enable the growth of these ventures.

2.3 Dynamic capabilities and entrepreneurial capabilities

Dynamic capabilities theory has garnered significant interest at the firm-level (Teece et al., 1997; Eisenhardt and Martin, 2000; Teece, 2007; Helfat and Peteraf, 2009). As this theory evolves, it is being recognised that the relationships between resources (tangible and intangible) and dynamic capabilities, and thus the links to firm performance may be more complex than initially assumed (Schilke et al., 2018). This is particularly relevant in the case of science-based university spin-offs during the pre-formation stage. Recent research demonstrates how the firm-level dynamic capabilities of sensing and shaping, and seizing, evolve from the pre-formation entrepreneurial capabilities of technology-market matching, claiming and protecting the invention, mentoring and strategic timing of firm formation, cumulatively leading to the emergence of well-endowed science-based university spin-offs (Thomas et al., 2020).

Pre- and early post-formation entrepreneurial capabilities can also have significant influence on the future success of the spin-off venture (Shane, 2004; Rasmussen et al., 2011), and are particularly important for academic scientists, as early, path-dependent decisions made in the lab affect technology development, scientific and business networks, and the path to commercial viability (Park et al., 2022). Several key pre-formation entrepreneurial capabilities that enable university spin-offs have been explored in the management literature. The first such capability, technology-market matching; involves the scientist-entrepreneur sensing and shaping initial and future market opportunities (Thomas et al., 2020; Park et al., 2022). Early market selection positively affects the future value capture of novel technologies (Gruber et al., 2008; Thomas et al., 2020), and strategic market prioritisation is particularly important for science-based ventures that operate under conditions of heightened uncertainty (Maine and Garnsey, 2006). Large sums of capital and long timelines are involved in the commercialisation of these ventures, thus, sound pre-formation decisions on market selection can de-risk and increase their potential for value capture (Maine et al., 2014; Gruber and Tal, 2017). In the pre-formation stage of science-based ventures, technology-market matching both precedes and supersedes opportunity recognition, product-market fit, or customer validation, as radical innovation generally involves opportunity creation rather than opportunity recognition (Maine et al., 2015).

Following the shaping of the opportunity, the other three pre-formation entrepreneurial capabilities are all ‘seizing’ capabilities (Thomas et al., 2020). They are: claiming and protecting the invention, attracting and mentoring the founding team, and strategic timing. Once the opportunity is shaped by the scientist-entrepreneur and her team, claiming and protecting the invention, generally through strategic patents, allows the venture to signal credibility to build partnerships and raise additional rounds of financing. Innovation scholars have investigated the influence of patenting on biotechnology firm success but have paid far less attention to the pre-formation capability of claiming and protecting the invention.

The next entrepreneurial capability of successful scientist-entrepreneurs is attracting and mentoring the founding team. The colleagues of scientist-entrepreneurs, who are often mentors and lab members, can be a part of and have influence on the cohesiveness and effectiveness of the future founding team (Murray, 2004). The capability to attract high quality and entrepreneurially minded students and business colleagues, and to mentor scientific lab members to become effective co-founders and venture employees, has a lasting impact on the success of the venture (Eesley et al., 2014; Thomas et al., 2020). This is both because the composition of the founding team has been found to have a persistent influence on firm performance (Eesley et al., 2014) and because the scientists who are mentored by the focal academic scientist co-founder are imprinted with her style and mindset (Beckman and Burton, 2008; Thomas et al., 2020).

The final pre-formation entrepreneurial capability is strategic timing. Particularly noted in scientist-entrepreneurs delaying firm formation, this capability serves to better align commercialisation timelines of science-based ventures with expectations of venture capital investors, who typically desire shorter timelines between investment and return on investment (Maine and Thomas, 2017; Thomas et al., 2020) and can also impact firm survival and performance.

While some studies linking intangible assets to investment-based metrics of biotechnology firms such as initial public offerings and financial analysts' earnings forecasts were identified (Gu and Wang, 2005; Fukugawa, 2012), we were not able to find any research in this sector that evaluated pre-formation intangible assets and explored how those assets led to firm performance. In particular, further research is needed to explicate how pre-formation intangible assets and entrepreneurial capabilities of the academic co-founders of science-based spin-offs work in tandem to contribute to firm performance.

3 Methodology

This paper explores the pre-formation intangible assets of three science-based university spin-offs now established in the biotechnology innovation ecosystem in British Columbia, Canada. Through detailed case studies, we analyse how intangible assets and entrepreneurial capabilities enabled their commercialisation success. To illustrate how these path-dependent decisions enabled the growth of these spin-offs, we collect and present data of related intangible assets that are linked to commercialisation success, drawing on work from Leitner (2005). Case studies allow for an in-depth exploration of our heavily nuanced context, which is needed to elucidate the complex factors that are related to science commercialisation (Eisenhardt, 1989; Etzkowitz, 1998; Yin, 2009). In particular, because the deployment of the pre-formation intangible assets and path-dependent decisions of academic scientist entrepreneurs are poorly understood (Druilhe and Garnsey, 2004; Rasmussen et al., 2011), it is necessary to employ a research method that allows for a multidimensional perspective.

Given our familiarity with the British Columbia biotechnology ecosystem, we identified a list of high value capture (i.e., revenue generating) firms in this sector. We further filtered this pool of firms by those that had ties to universities (to investigate the influence of pre-formation intangible assets on spin-offs) and sorted them by annual revenue ten years after firm founding, for consistency.

While all firms within the biotechnology sector are generally characterised by high levels of uncertainty (Pisano, 2006b, 2010; Maine and Seegopaul, 2016), we selected within this subgroup three firms that further span the spectrum of technology and market uncertainty by drawing from Maine and Seegopaul (2016), who note that biotechnology ventures that undergo clinical trials (i.e., therapeutics firms) have to endure particularly high uncertainty and long timelines to commercialisation. Therefore, we categorise our therapeutics case firm AbCellera as the firm with the highest uncertainty. We chose another supplier firm that manufactures reagents for lab research (StemCell Technologies) and another that is an instrumentation venture (Precision NanoSystems), which represent lower levels of uncertainty than AbCellera. By selecting firms of varying uncertainty, cross-case comparison is enabled, examining both similarities and differences in the role of pre-formation intangible assets and entrepreneurial capabilities as uncertainty increases and revealing which intangible assets and entrepreneurial capabilities enable firm performance in this ecosystem.

Secondary data was gathered on these firms from their websites, press releases, their papers in academic journal databases including Scopus, Google Patents, Lens, and personal communications with current and former executives and founders. Data related to pre-formation intangible assets include lists of papers, patents, and the co-authors and co-inventors of papers and patents, respectively and revenue ten years after firm founding. These data were collected and calculated through adapting a set of proxies of intangible assets suggested by Leitner (2005). Data related to pre-formation entrepreneurial capabilities include evidence of early technology-market matching (e.g., through press releases, interviews, licensing agreements and more), and other key events prior to incorporation (with a focus on evidence of mentoring, claiming and protecting the invention, and delaying firm formation or prolonged incubation in a university setting). To inform our case studies, we compare the results of the data collection of pre-formation intangible assets and entrepreneurial capabilities to revenue ten years after firm founding.

4 Findings

In this section we discuss our findings based on case studies of three British Columbia-based biotechnology firms: StemCell Technologies, Precision NanoSystems, and AbCellera. We choose these three firms as they are all examples of high value creation firms (measured by revenue and other successful commercial events such as acquisitions and IPOs). We examine how intangible assets and entrepreneurial capabilities enabled these firms' financial performance. The data referred to throughout this section are presented in Table 1. The data fields collected for each firm are shown in Table 2a and the sources utilised to compile the data are summarised in Table 2b.

Table 1 Pre-formation intangible assets and entrepreneurial capabilities of academic scientist co-founders

			Firm				
Components			*StemCell Technologies*		*Precision NanoSystems*		*AbCellera*
Academic scientist co-founders			*Allen Eaves*	*Connie Eaves*	*Pieter Cullis*	*Carl Hansen*	*Carl Hansen**
Intangible assets (antecedents)	International networks	% affiliation from different country	88%	89%	62.2%	60%	48.20%
		# affiliations	17	19	74	20	27
	Research excellence	# pre-formation papers	70	91	279	17	40
		# all-time papers	138	309	357	65	65
	# patents	# pre-formation patents	0	0	203	8	32
		# pre-formation patents (simple families)	0	0	67	1	4
		# all-time patents	0	14	223	73	82
		# all-time patents (simple families)	0	10	73	11	11
Entrepreneurial capabilities	Technology-market matching		Yes		Yes		Yes
	Claiming and protecting the invention		No		Yes		Yes
	Attracting and mentoring the founding team		Yes		Yes		Yes
	Strategic timing of firm formation		No		No		Yes
Spin-off endowment intangible assets	Co-development/beta-testing		Yes		Yes		Yes
	# pre-formation patents linked to spin-off		0		1		2
	# pre-formation papers linked to spin-off		10+		2		10
	Mentored scientist employees		Yes		Yes		Yes
10-year revenue CAD (estimated)			$72M**		$16M		$69.4M***

Notes: *Hansen's number of publications/patents are higher for AbCellera because of the later founding date.
**StemCell's 2003 revenue was estimated by triangulating and interpolating published revenue data from close and/or adjacent years.
***Full year 2020 data.
****All-time paper and patent data collected as of December 2021.

Table 2a Data collected for each firm

Data field	*Data type*	*Pre- or post formation*	*Description (if applicable)*
Firm founding year	Integer		
Firm revenue ten years after firm formation	Float	Post	
Intangible assets			
Number of co-authors of papers	Integer	Pre	Co-authors listed by journal indexing databases
Number of co-inventors of patents	Integer	Pre	Co-inventors listed by Google patents
Number of papers	Integer	Pre	Peer-reviewed, academic paper publications
Number of patents	Integer	Pre	Granted patents
Number of external co-authors of papers	Integer	Pre	Co-authors affiliated with an external institution
Number of international co-authors of papers	Integer	Pre	Co-authors affiliated with an international institution
Entrepreneurial capabilities			
Technology-market matching	Boolean	Pre	Existence of evidence of early market selection
Attracting and mentoring founding team	Boolean	Pre	Existence of evidence of attracting and entrepreneurial mentoring of graduate students, or receiving entrepreneurial mentorship as a graduate student
Claiming and protecting the invention	Boolean	Pre	Existence of pre-formation patent that has direct relevance to firm technical capabilities
Strategic timing of firm formation	Boolean	Pre	Evidence that founders delayed firm formation to better meet investor timeline expectations

4.1 StemCell Technologies

Founded by Dr. Allen Eaves (A. Eaves) in 1993, StemCell Technologies manufactures cell culture media, reagents, instrumentation and offers contract research services to researchers and institutions for stem cell, immunology and related biological research. As of 2021, it is the largest biotechnology company in Canada, employing more than 1,500 people in 12 countries, with revenues estimated at $226 M (BIV Life Sciences, 2021). StemCell has its roots in the Terry Fox Laboratories, which was founded in 1981 by A. Eaves and his wife, Dr. Connie Eaves. Terry Fox Laboratories is a partnership between the BC Cancer Agency, the University of British Columbia and the National Cancer Institute of Canada and is focused on developing novel experimental models for human cancer research. While conducting their initial research, Drs. Allen and Connie

Eaves found existing commercial cell cultures unsatisfactory and began developing and selling their own, which represented the genesis of StemCell.

Table 2b Supporting information and data sources

Categories	*Ventures*	*Name of the source*	*Sources*
Biotech type	StemCell Technologies	Journal article	Maine, E., Thomas, V.J., Bliemel, M., Murira, A. and Utterback, J. (2014) 'The emergence of the nanobiotechnology industry', *Nature Nanotechnology*, Vol. 9, No. 1, pp.2–5.
International networks		Scopus.com	https://www.scopus.com/authid/detail.uri?authorId=7101806471
Research excellence		Scopus.com	https://www.scopus.com/authid/detail.uri?authorId=7101806471
# patents		Lens.org	https://link.lens.org/KovzMGcrQLh
			https://link.lens.org/hOkZuifjinh
			https://link.lens.org/EQbst7pmicb
Technology-market matching		StemCell website	https://www.stemcell.com/about-us/letter-from-our-founder
Mentoring		Interview, A. Eaves	https://www.youtube.com/watch?v=FkWvLfDrEZk
Claiming and protecting		Lens.org	https://link.lens.org/F0VkUSb6Wne
Product commercialised		StemCell website	https://www.stemcell.com/about-us/letter-from-our-founder
10-year revenue		Various sources	https://biv.com/article/2013/03/allen-eaves-cell-division
		Various sources	https://lifesciencesbc.ca/wp-content/uploads/2021/03/Creative-Financing.pdf
# patents assigned to the firm		Lens.org	https://link.lens.org/F0VkUSb6Wne
# international sales		The Canadian Business Quarterly	https://thecbq.ca/stemcell_technologies_ceo_president_allen_eaves_canadas_regenerative_medicine_company/
Biotech type	Precision NanoSystems	Journal article	Maine, E., Thomas, V.J., Bliemel, M., Murira, A. and Utterback, J. (2014) 'The emergence of the nanobiotechnology industry', *Nature Nanotechnology*, Vol. 9, No. 1, pp.2–5.
International networks		Scopus.com	https://www.scopus.com/authid/detail.uri?authorId=26030939400
Research excellence			https://www.scopus.com/authid/detail.uri?authorId=7101856304
# patents		Lens.org	https://link.lens.org/r0Cg7sYRQdj
			https://link.lens.org/gVb4IxIgUbj

Table 2b Supporting information and data sources (continued)

Categories	*Ventures*	*Name of the source*	*Sources*
Technology-market matching	Precision NanoSystems	Precision NanoSystems website and Private conversation with Dr. Cullis	https://www.precisionnanosystems.com/news-room/detail/pni-alnylam-new-delivery-collaboration
Mentoring the founding team		Dr. James Taylor PhD thesis	UBC Library
Claiming and protecting the invention		Lens.org	https://link.lens.org/r0Cg7sYRQdj https://link.lens.org/gVb4IxIgUbj
Product commercialised		Precision NanoSystems website	https://www.precisionnanosystems.com/platform-technologies/product-comparison
10-year revenue		dnb.com	https://www.dnb.com/business-directory/company-profiles.precision_nanosystems_inc.65ce1f7ab736119c0b3c3284900f1601.html
# patents assigned to the firm		Lens.org	https://link.lens.org/KrpWGH5FHrk
Biotech type	AbCellera	Journal article	Maine, E., Thomas, V.J., Bliemel, M., Murira, A. and Utterback, J. (2014) 'The emergence of the nanobiotechnology industry', *Nature Nanotechnology*, Vol. 9, No. 1, pp.2–5.
International networks	AbCellera	Scopus.com	https://www.scopus.com/authid/detail.uri?authorId=26030939400
Research excellence			https://www.scopus.com/authid/detail.uri?authorId=7101856304
# patents		Lens.org	Associated weblink/s
Technology-market matching		Pre-formation paper	Singhal, A., DaCosta, D., Haynes, C. and Hansen, C. (2011) 'A microfluidic platform for screening and selection of monoclonal antibodies from single cells', in *15th International Conference on Miniature Systems for Chemistry and Life Sciences*, October, Vol. 2, pp.323–325.
Mentoring the founding team		AbCellera website and phas.ubc.ca	https://phas.ubc.ca/phas-researcher-carl-hansen-leads-ubc-biotechnology-spin-abcellera
Strategic timing		Journal article	Park, A., Goudarzi, A., Yaghmaie, P., Thomas, V.J. and Maine, E. (2022) 'Rapid response through the entrepreneurial capabilities of academic scientists', *Nature Nanotechnology*, Vol. 17, No. 8, pp.802–807, https://doi.org/10.1038/s41565-022-01103-6

Table 2b Supporting information and data sources (continued)

Categories	*Ventures*	*Name of the source*	*Sources*
Claiming and protecting the invention		AbCellera website	https://investors.abcellera.com/news/news-releases/2019/AbCellera-Announces-the-Issuance-of-Foundational-Patent-Claims-Around-Microfluidic-Screening-Assays-for-Antibody-Discovery/default.aspx
Product commercialised		AbCellera website	https://investors.abcellera.com/news/news-releases/2020/AbCellera-Discovered-Antibody-Receives-U.S.-FDA-Emergency-Use-Authorization-as-a-Monotherapy-for-the-Treatment-of-COVID-19/default.aspx
10-year revenue		AbCellera website	https://s26.q4cdn.com/359178033/files/doc_financials/2020/q4/AbCellera-2020-Business-Update-(March-29-2021).pdf
# patents assigned to the firm		AbCellera website	https://d18rn0p25nwr6d.cloudfront.net/CIK-0001703057/2f536b97-887a-4acd-9a86-6de7fc0440b0.pdf (page 30, UBC core patents)

Drs. Allen and Connie Eaves have both held academic appointments, including Professorships in Medicine, Pathology and Medical Genetics at the University of British Columbia. Prior to the formation of StemCell, both Drs. Allen and Connie Eaves demonstrated the possession of important intangible assets. For example, Connie Eaves exhibited research excellence with 91 publications in scientific journals, including in elite journals such as Nature, Cancer Research, and Blood, closely followed by A. Eaves with 70 publications. They also maintained an impressive network of external collaborations, with 89% and 88% of co-authors of these publications coming from institutions outside of which Drs. Connie and Allen Eaves were employed, respectively.

Furthermore, over 10% of co-authors in papers from both researchers were colleagues outside of Canada, demonstrating the breadth and international makeup of their networks. The richness of the founders' international networks is also evidenced by the composition of the company's initial customers, many of whom were academic researchers outside Canada. StemCell specifically identified academic researchers as their target customer, with the aim of supplying them quality products to support their research (Vancouver Sun, 2018). Most of the company's early customers were outside Canada and included scientists from renowned research institutions such as Baylor College of Medicine, Boston Children's Hospital and Harvard University (Lens.org, 2022).

In addition to intangible assets, both Drs. Allen and Connie Eaves demonstrated the possession of technology-market matching and mentoring entrepreneurial capabilities. As briefly described in the introduction of this subsection, A. Eaves observed the poor quality of commercially available cell culture reagents during his early research years at the Terry Fox Laboratory. He recognised the market potential of selling carefully crafted, high quality media for culturing hematopoietic stem cells. Realising the vast potential of this market, A. Eaves purchased this particular application (manufacturing and selling reagents for stem cell and immunology research) from the Terry Fox Laboratory, secured a loan from Western Economic Diversification and mortgaged his home to found StemCell Technologies (EuroStemCell, 2020).

The founders have a longstanding reputation of receiving and placing importance on mentoring. Connie Eaves received very close mentorship from her doctoral supervisor, Dr. Lazlo Lajtha at the Paterson Laboratories of the Christie Hospital and the Holt Radium Institute in the UK. Working with Dr. Lajtha, Connie Eaves made a seminal discovery in 1968, namely the existence of B and T lymphocytes. Since then, Connie Eaves has demonstrated mentoring of her own students. Over the past several decades, she has been the primary mentor for over 90 graduate students and post-doctoral fellows (The Canadian Cancer Research Conference, 2017), many of whom have become prominent biological scientists themselves. The impetus for founding StemCell was for Allan and Connie Eaves to create jobs for their former students. StemCell as an organisation also clearly places value on graduate training, as over one-third of its more than 1,400 employees hold a PhD, and over two-thirds hold an advanced degree (StemCell Technologies, 2021).

This combination of intangible assets and entrepreneurial capabilities (specifically, technology-market matching and mentoring) contributed to the success that StemCell is enjoying today. In addition to being the largest biotechnology company in Canada, StemCell has achieved numerous other milestones and achievements, including a $45 million federal and provincial government grant to build an advanced manufacturing facility in 2018, and notable partnerships with incumbent healthcare firms such as ENKAM Pharma and GE Healthcare to further develop and expand their cell therapy product line. StemCell has also significantly expanded its intellectual property portfolio, having accumulated 27 granted patents as of 2021. Notably, StemCell sells 97% of its products internationally (National Research Council Canada, 2021).

4.2 Precision NanoSystems

Precision NanoSystems was founded jointly by Dr. Pieter Cullis (Professor, University of British Columbia), Dr. Carl Hansen (also of AbCellera and Associate Professor, University of British Columbia until 2019). Cullis and Hansen attracted two other scientist co-founders, Dr. James Taylor (PhD, Institute for Systems Biology, Seattle, WA) and Dr. Euan Ramsay (PhD, Cardiff University), to take on the CEO and COO roles, respectively. The company was a natural extension of Cullis' pioneering work in lipid nanoparticles, which allow therapeutics such as drugs, or genetic material packaged in several lipid layers to more easily bypass the cell lipid bilayer, allowing for more efficient delivery of the encapsulated therapeutic. Precision NanoSystems developed branded instrumentation known as the NanoAssemblr, which enabled rapid and predictable mixing of lipid molecules with a therapeutic of interest, and these instruments were sold to research institutions across the world.

Precision NanoSystems also exemplified the importance of possessing pre-formation, knowledge-based intangible assets in enabling future commercial success. Dr. Pieter Cullis is a world-renowned biophysicist, whose early work in discovering and developing of lipid nanoparticles garnered him international acclaim, and his research excellence is evidenced by over 250 scientific articles, published before Precision NanoSystems was founded in 2010. His research has been published multiple times in elite journals such as Science, Nature Biotechnology and Cancer Research. His collaborations with external networks are rich and expansive; more than half of his research publications included co-authors from countries outside of Canada and he had commercial collaborations with 24 local and international firms before the incorporation of Precision NanoSystems. Precision NanoSystems (2021b) has maintained its research excellence to this day, with over 500 peer-reviewed journal articles published by its leadership team. He is also the only serial star scientist-entrepreneur among our exemplars, having founded or co-founded four biotechnology firms starting with the Canadian Liposome Company in 1987. The firm's founding team further demonstrate its extensive knowledge-based pre-formation intangible assets, as evidenced by the accumulation of 80 US patents between Dr. Pieter Cullis and Dr. Carl Hansen.

Similar to AbCellera and StemCell Technologies, Precision NanoSystems' founders demonstrated the importance of key technology-market matching, claiming and protecting the invention and mentoring entrepreneurial capabilities. Prior to spin-off formation, Cullis recognised the market potential of encapsulating nucleic acids in lipid nanoparticles, especially if he were able to provide a method to generate high precision, rapid throughput molecules for other researchers conducting drug delivery research. However, the full potential of his solution was limited by the fact that Cullis was not yet able to achieve the necessary high accuracy mixing results at scale.

Perhaps serendipitously, Cullis discussed his challenges with Hansen, who suggested that Cullis try microfluidic mixing in parallel to achieve high accuracy mixing at large volumes (P. Cullis, personal communication, 5 May 2021). This encounter served as a springboard for the development of the NanoAssemblr platform and was necessary for Cullis to realise that the envisioned research market for his core lipid nanoparticle technology could indeed be served. The early recognition of the potential of lipid nanoparticles informed the entrepreneurial capability of claiming and protecting the invention – observed through the fact that Cullis patented this technology many years before the company was incorporated. This patent on the platform technology on lipid nanoparticles became a credible pre-formation intangible asset, endowing Precision NanoSystems.

There is also strong evidence of mentoring among the company's founding team. Both Hansen and Taylor completed a portion of their graduate training at the Institute for Systems Biology, and Hansen in particular was influenced by the renowned scientist-entrepreneur, Dr. Leroy Hood. Relatedly, Taylor's PhD dissertation was supported and mentored by Hansen (Taylor, 2009). Cullis also acknowledges the importance of longstanding, deep collaborations and mentorship, specifically noting that accumulated knowledge compounds, and that Precision NanoSystems has benefited from the fact that the key founders resided in Vancouver, and had been collaborating for several years prior to founding. He notes that while the firm has enjoyed much recent success, it is the product of multiple decades of deep personal collaboration (P. Cullis, personal communication, 5 May 2021).

The combination of knowledge-based intangible assets and entrepreneurial capabilities (specifically technology-market matching, claiming and protecting the invention and mentoring) have contributed to Precision NanoSystems being one of the fastest growing nanobiotechnology companies in North America. By 2019 they had sold over 280 systems worldwide, used by over 95 pharma/biotech and 90 academic customers. Subsequently PNI signed a critical licensing agreement with pharmaceutical giant Daiichi Sankyo to help produce its therapeutics at scale, using the NanoAssemblr system (T-Net, 2019). Although PNI started with a focus on providing instrumentation for the life sciences sector, their expertise in the field of Lipid Nanoparticles (LNPs, delivery agents for the COVID-19 mRNA Vaccines) can be extended to other types of genetic materials and nucleic-based drug modalities. In early 2021, PNI received $25.1 million CAD from the Government of Canada Strategic Innovation Fund (SIF) to establish a GMP biomanufacturing facility in Vancouver focused on the large-scale production of RNA lipid nanoparticles (Precision NanoSystems, 2021a) which shifted their position toward a therapeutic enabler firm rather than an instrumentation manufacturer. The company's recent success hit a high-water mark in June 2021, where it was announced that Danaher, a multinational medical and life science product supplier with a market capitalisation of over $231B, acquired Precision NanoSystems for an undisclosed sum (BIV, 2021).

4.3 AbCellera

AbCellera was co-founded in 2012 as an end-to-end antibody solutions company by Dr. Carl Hansen (Hansen), who had been developing AbCellera's antibody discovery technology for more than a decade before the company's formation, beginning as a PhD student at the California Institute of Technology, and later as a professor at the Department of Physics and Astronomy at the University of British Columbia. It is during this pre-formation period that Hansen, his lab members and collaborators, including Veronique Lecault, Kathleen Lisaingo and Kevin Heyries, developed their significant stock of intangible assets.

For example, the foundation of AbCellera's platform is based on a microfluidic technology that allows for rapid detection of antibodies within hours, compared to the incumbent process which can take weeks (AbCellera Biologics Inc., 2020). This technology was the foundation for AbCellera's co-development of *bamlanivimab* with Eli Lilly, which became the first FDA emergency-use authorised therapeutic in response to COVID-19 (AbCellera, 2021). We find evidence of Hansen developing knowledge-based intangible assets prior to firm formation through two key patents related to microfluidics (US 10,421,936; US 10,274,494). Furthermore, we identified several key papers related to microfluidics in top tier scientific journals written by Hansen and his academic colleagues, which were published several years before firm formation, further demonstrating the acquisition of intangible assets and demonstrating research excellence.

We also find evidence of the importance of broad, international networks in Hansen's development of his antibody solutions platform. Hansen's collaboration and involvement with fluidigm, which was a university spin-off venture founded by his PhD supervisor in the USA, was critical not only in providing Hansen early experience in entrepreneurship, but also in further developing Hansen's expertise in microfluidics, as fluidigm pioneered microfluidics instrumentation specifically in biological research. We see a further example of Hansen's acquisition of intangible assets through international networks in academic publications: out of 40 published scientific articles prior to the founding of AbCellera, nearly half of his co-authors were based outside of Canada (Table 1).

In addition to intangible assets, we observe the importance of Hansen's entrepreneurial capabilities: early technology-market matching, claiming and protecting the invention, mentoring, and strategic timing of firm formation. While microfluidics has a broad set of applications, Hansen recognised the potential of matching microfluidics specifically to the antibody market early during technology development while working with his graduate students in the mid 2000s. Furthermore, Hansen negotiated an exclusive license of his microfluidics platform with the University of British Columbia (2013), specifically for the antibody field of use. He took further steps to strategically patent this technology prior to firm formation, in collaboration with his university-industry licensing office, showing evidence of early claiming and protecting of his invention.

Hansen both benefited from, and provided, early mentorship, which had crucial downstream benefits in AbCellera's success. Hansen was mentored by star scientist-entrepreneur Dr. Stephen Quake during his PhD, which not only provided him significant technical expertise in microfluidics, but also exposure to entrepreneurship through Quake's start-up, Fluidigm. Hansen then mentored his own graduate students and post-doctoral fellows at the University of British Columbia. Both mentorship periods conferred significant future benefits to AbCellera: because of Hansen's familiarity with the company, he maintained collaborative research agreements with fluidigm while developing AbCellera's technology at the University of British Columbia. Also, several of Hansen's former PhD students and post-doctoral fellows now hold senior leadership positions at AbCellera.

Hansen also showed strategic timing of firm formation. AbCellera was incorporated six years after the initial development of Hansen's microfluidics platform. This allowed AbCellera further de-risking the technology in a university setting, shortening Abcellera's time to commercialisation to better align with return of investment targets of venture capital investors. AbCellera successfully began raising financing shortly after its incorporation. Even after incorporation, AbCellera incubated within the university environment, maintaining its offices at the University of British Columbia for several years, allow it to focus on science, rather than operational overhead activities that are often required of start-up ventures, which cost money and can sometimes distract busy scientific co-founders.

The intangible assets (international networks, research excellence, patenting) and entrepreneurial capabilities (technology-market matching, claiming and protecting the invention, mentoring and strategic timing of firm formation) described in this case played critical roles in AbCellera's commercialisation success. In addition to co-developing the first FDA emergency use authorised (EUA) therapeutic for COVID-19, AbCellera has secured over 100 biotechnology partners who provided consistent revenue to fund its growth. Moreover, AbCellera received US$126M from the Government of Canada to not only discover antibodies, but to also build a facility to manufacture them at scale (Innovation, Science and Economic Development Canada, 2020). Lastly, AbCellera recently conducted the largest Canadian biotechnology IPO in history with an initial valuation of over US$12B (Silcoff, 2020).

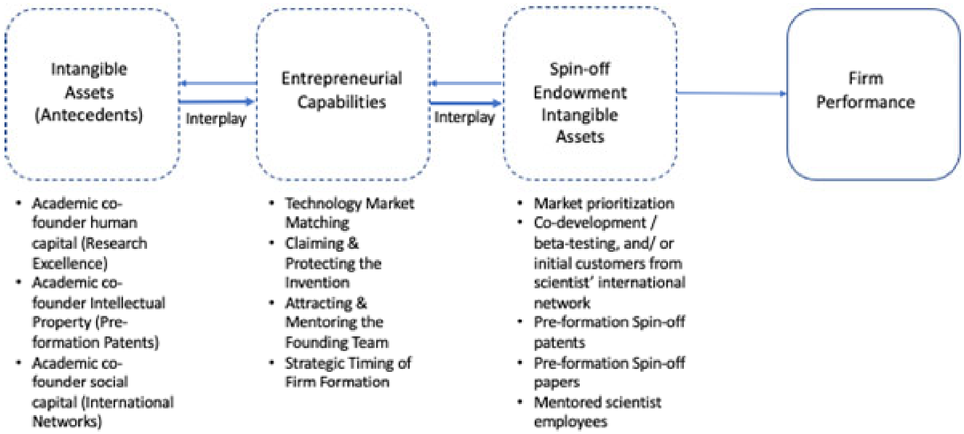
5 Discussion

Science-based ventures, particularly those emerging from university settings, face significant challenges on the road to commercialising breakthrough technologies with societal impact. Our findings demonstrate that the biotechnology firms that survive and have high levels of performance in this sector leverage pre-formation intangible assets such as the patents, research excellence and the international networks of the academic co-founders. We demonstrate how academic co-founders can develop and deploy entrepreneurial capabilities to generate firm-specific intangible assets prior to venture formation which impact firm survival and success over the longer term. We propose a model (Figure 1) which elucidates how academic scientists enable the interplay of pre-formation intangible assets and entrepreneurial capabilities to endow science-based university spin-offs.

5.1 Pre-formation intangible assets: necessary but insufficient

While extant research has often suggested that academic scientists may lack the skills needed for science commercialisation (Gurdon and Samsom, 2010), other scholars observe that academic scientists have rich and deep collaboration networks which can be measured through proxies such as patents and papers (Murray, 2004; Schiffauerova and Beaudry, 2009, 2012). Our evidence supports the latter view and that these collaboration networks can be considered as pre-formation intangible assets which can be leveraged to endow university spin-offs. As shown in Table 1, all three cases have substantial pre-formation intangible assets in the form of research excellence, patents, and international networks. All three cases feature prolific scientists, well published and with extensive and international networks. In two of the cases, the academic scientists are also inventors on granted patents prior to firm formation, with one star-scientist entrepreneur having an extensive patenting history. We further observe the importance of international networks, most prominently in the case of StemCell Technologies, where their customer base was comprised primarily of academic scientists from international research institutions. Despite the impressive stock of intangible assets, the leveraging of such *pre-formation* intangible assets is not a given.

Figure 1 The role of pre-formation intangible assets in endowing science-based university spin-offs (see online version for colours)



Note: Dotted lines denote pre-formation intangible assets and entrepreneurial capabilities.

While a robust body of research investigating the breadth and utility of academic and international networks exists (e.g., Bolzani et al., 2021; Pitt et al., 2021; Beaudry and Schiffauerova, 2011), there is a significant gap in the corpus of literature that directly links the characteristics of these networks to firm performance. This is likely due to the difficulty in conceptually and empirically examining these linkages, given that the impact of *pre-formation* collaboration networks of academic scientist co-founders on *post-formation* venture performance is understudied. A deeper investigation of these linkages is germane to the context of scient-based university spin-offs facing high levels of technology and market uncertainty, as firms operating under these conditions have limited resources and must rely on external sources of knowledge and technical and commercial capabilities (Niosi, 2003; Baum and Silverman, 2004).

5.2 Entrepreneurial capabilities: focusing pre-formation intangible assets to become spin-off endowment intangible assets

Employing a cross-case comparison, the role of entrepreneurial capabilities in *focusing* pre-formation intangible assets to become spin-off endowment intangible assets is demonstrated. The pre-formation entrepreneurial capability of *technology-market matching* offers a mechanism to focus these broad and deep intangible assets on specific market applications, ideally prior to venture formation. Evidence of pre-formation technology-market matching by the academic scientist was observed in all three university spin-offs. The agency of the academic scientist is critical during this pre-formation stage, though it should be emphasised that scientific development is done along with lab members and other scientific collaborators both within and outside the parent university (Murray, 2004; Rasmussen et al., 2011; Thomas et al., 2020). Beyond scientific development, technology-market matching, though primarily led by the academic co-founder, may be informed by the experience and perspectives of members of the scientist's collaboration networks and institutional support systems such as the university technology licensing office. For example, in the case of StemCell Technologies, Allen Eaves was encouraged to form a venture to produce stem cell reagents by members of the BC Cancer Foundation (EuroStemCell, 2020). In the case of Precision NanoSystems, a casual meeting between Dr. Cullis and Dr. Hansen was the catalyst for the technical development of its NanoAssemblr platform. For AbCellera, Dr. Hansen gained insights into microfluidics commercialisation through his time in the lab of Dr. Quake during his PhD. Both the early timing of this entrepreneurial capability and the involvement of a scientist's research networks are underappreciated in literature and practice. This entrepreneurial capability of technology-market matching leads to two spin-off endowment intangible assets: market prioritisation and co-development/beta testing (Table 1 and Figure 1). Such early and strategic market prioritisation has been shown to be pivotal to value creation and capture by science-based ventures (Maine and Garnsey, 2006; Gruber et al., 2008; Thomas et al., 2020). Co-development and beta testing demonstrates the value of the academic scientist's deep international collaboration network, when mobilised to focus on a prioritised market.

The other three entrepreneurial capabilities all contribute to seizing the opportunities created from the matching of novel technologies to unmet market needs. *Claiming and protecting the invention* was observed in 2 of the 3 case studies – notably those facing higher levels of uncertainty. Patents can be used by science-based ventures to signal the ability to appropriate value to investors (Hsu and Ziedonis, 2008; Maine and Thomas, 2017; Park, 2021). If such patents are broad, blocking, and relevant in nature, there is increased potential to achieve higher levels of value capture (Maine and Thomas, 2017; Thomas et al., 2020). As depicted in Table 1, two spin-offs were endowed with intangible assets in the form of foundational patents which were licensed into their ventures and provided credibility and signalled the potential for appropriability and value capture.

An underappreciated mechanism for mobilising intangible assets to enhance firm performance, *mentoring the founding team* was observed in all three case studies, with long term supervisory and collaboration relationships of junior scientists to the academic co-founder and their network endowing the spin-off with trusted and high-quality scientific co-founders and employees with deep tacit knowledge. Researchers have observed that the impact of founders on firm success can last well beyond the tenure of the founders (Beckman and Burton, 2008). Extending this idea to the pre-formation stage of science-based university spin-offs, Thomas et al. (2020) suggest that such founder imprinting can also occur in the research lab through mentoring by the star scientist-entrepreneur for his graduate students. Graduate training is an intense period of research activity and the transference of disciplinary norms. Drawing on the case of a star scientist-entrepreneur, Thomas et al. (2020) show how such mentoring in the research lab builds trust and knowledge which is valuable during the early stages of science-based spin-off emergence. Table 1 shows how the academic scientist co-founder of the highest uncertainty venture, AbCellera, mentored members in his lab who later went on to become co-founders and senior leaders of AbCellera as it grew. For each case study venture, future scientific employees were frequently alumni from the labs of the academic co-founders. In this manner, the pre-formation intangible assets of the academic co-founders such as the international research collaboration networks, patents, and papers with members of his lab and collaborators were leveraged to develop specific endowment assets such as spin-off patents which then could be used to signal credibility and potential for value capture.

There can often be a mismatch between the timelines of investors and scientist-entrepreneurs. Academic scientists with limited prior experience of launching spin-offs may have an overly optimistic view of technology development which then can lead to inordinate delays in commercialisation post-formation. Recent studies suggest the entrepreneurial capability of *strategic timing of firm formation* as a technique to better match technology development to the funding timelines of investors (Maine and Thomas, 2017; Thomas et al., 2020). Table 1 depicts that this entrepreneurial capability was only observed in the case of the spin-off facing high levels of uncertainty as a therapeutics enabler. AbCellera, the therapeutics-enabler spin-off, engaged in significant technology refinement and market assessment and prioritisation well before venture formation. The academic co-founder secured multiple patents and papers specifically linked to the microfluidic technology for rapid detection of monoclonal antibodies which acted as pre-formation endowment assets. The impact of these valuable endowment assets is evident in the survival and performance data for AbCellera which indicates that even in a situation with persistently high levels of technology and market uncertainty, AbCellera was able to achieve significant revenues exceeding its older and more established peers from the same innovation ecosystem.

5.3 Impact of pre-formation entrepreneurial capabilities and spin-off endowment intangible assets on firm performance

Science-based university spin-offs often struggle to survive, and researchers have noted that most science-based are likely to fail in the first decade (Timmons, 1990; Dimov and De Clerq, 2006). This is commonly due to the higher levels of technology and market uncertainty or the lack of business skills of academic scientists (Gurdon and Samsom, 2010). Thus, our study which examines the 10-year survival status, and the 10th year revenue of the selected biotechnology spin-off sets a high bar for the measurement of firm performance particularly for spin-offs emerging from a university setting (Table 1). Also notable is the fact that the youngest spin-off AbCellera has faced the highest levels of uncertainty as a therapeutics enabler firm and yet has managed to significantly outperform the other two case study spin-offs in terms of annual revenue. The evidence in Table 1 shows that AbCellera is the only spin-off that has demonstrated all four entrepreneurial capabilities. The nuanced evidence presented in Table 1 suggests that entrepreneurial capabilities play a central role in leveraging pre-formation intangible assets which lead to the development of valuable spin-off endowment assets. The path-dependent nature of such endowments impacts firm survival and long-term performance even in the face of high levels of technology and market uncertainties.

5.4 Implications for theory

We contribute to the technology management literature by elucidating the roles pre-formation intangible assets and entrepreneurial capabilities play in enhancing firm performance. More specifically, we respond to Schilke et al.'s (2018) assertion that there exists a research gap with respect to agency in dynamic capabilities research, i.e., the conditions under which managers are able to alter their own and their organisations' trajectories. We contextualise our research within science-based university spin-offs, which are uniquely characterised by inordinately high research and development costs and commercialisation timelines (Maine and Seegopaul, 2016), which may, on cursory examination, suggest that managers may find it difficult to affect change.

We extend Schilke et al.'s (2018) organisational framework of dynamic capabilities by elucidating the mechanism through which managers (in our context, academic scientist co-founders) deploy agency through intangible assets (Figure 1). This mechanism is enabled by entrepreneurial capabilities, which are critical given the high uncertainty environment under which science-based firms operate. For example, claiming and protecting the invention, manifested through pre-formation patenting, in addition to conferring the obvious benefits of knowledge creation, IP protection and freedom-to-operate, generate positive reputational signals, which have been shown to draw investor interest and improve the probability of other biopharmaceuticals firms to in-license the embodied knowledge (Hsu and Ziedonis, 2008; Ruckman and McCarthy, 2016).

In other words, our findings suggest that entrepreneurial capabilities help academic scientists to mobilise these pre-formation intangible assets. It is such a relationship that Schilke et al. (2018) have noted is understudied and under identified in the dynamic capabilities' literature, and thus represents another contribution to the field. For example, we observe the importance of pre-formation mentoring in firm survival and performance, particularly when the student being mentored is still in the founder's lab. This early guidance establishes a high level of trust and technical know-how, the benefits of which can compound as the science-entrepreneur commercialises and grows their venture (Thomas et al., 2020). Our findings are related to work by Eesley et al. (2014), who find that the early configuration and combination of specific skills and expertise have pronounced effects on future firm performance.

5.4.1 Intangible assets: pre-formation vs. post-formation

While we focus on pre-formation intangible assets, entrepreneurial capabilities, and spin-off endowment intangible assets, which by their nature are related to activities and resources available prior to, and in the early stages of venture formation, we acknowledge that there is a growth-accounting stream of research that centres on large, existing firms, post-formation. For example, Corrado et al. (2005) offer methods by which established and growing firms can quantify and incorporate intangible assets into their balance sheets, which the authors broadly categorise into investments in computerised information, innovative property, and economic competences. The same authors extend this logic in a macroeconomic fashion, aggregating the spending metrics of firms to re-evaluate US GDP data (Corrado et al., 2009).

However, the methodologies employed in these growth-accounting papers are predicated on spending metrics by well-established firms, who have already survived and crossed the valley of death (US Department of Energy, 1991), which may not be as relevant to the pre-formation intangible assets and entrepreneurial capabilities we examine in this paper. Our focus is on the intangible assets that enable the formation of university spin-offs, which is more consistent with the early-stage intangible assets literature (Aizcorbe et al., 2009; Heirman and Clarysse, 2007; Huang et al., 2011). In the case of biotechnology firms, it may be many years before a venture enjoys significant revenues, given the extended timelines associated with R&D and clinical trials (DiMasi et al., 2010; Pisano, 2010).

As the firms in our cross-case comparison continue to grow and become the incumbents in their respective subsectors, the spending metrics and alternative lens through which scholars like Corrado et al. quantify intangible assets becomes more relevant and represent interesting avenues for follow up research. For example, Florin et al. (2003) investigate the role of human and social capital in firm performance both in the early stages and after an IPO. This longitudinal approach may be of interest to scholars wishing to examine how the effects of intangible assets on firm performance differ between the pre-formation and post-maturation stages. Indeed, we see that after ten years after firm formation, the exemplars in our study begin to experience appreciable revenues (Table 1). However, even close to the 10-year mark, a highly uncertain firm such as AbCellera may be unsure of the economic value they will generate. For example, in 2020 the company noted they were not certain when they would receive significant royalty payments from their drug discovery partnerships (AbCellera Biologics Inc., 2021).

5.5 Implications for practice

We make several recommendations for scientist-entrepreneurs who wish to commercialise a novel technology with high levels of uncertainty. Pre-formation intangible assets (specifically research excellence, patenting, and international networks), when focused through entrepreneurial capabilities better endow science-based university spin-offs and supports higher levels of firm performance. Scientist-entrepreneurs can benefit from enrolling in entrepreneurial education programs tailored to shaping science innovation, such as Invention to Innovation (Beedie School of Business, Simon Fraser University) and Cyclotron Road (Berkeley National Laboratory). These science-focused programs provide basic training in technology-market matching and intellectual property protection (i.e., patenting) and allow for the expansion of external networks by facilitating collaborations with other scientist-entrepreneurs and industry mentors. Crucially, these programs are most effective when shaping the innovation idea and when the learning's of the academic scientist and their lab members can feed back into market-informed research priorities which can generate social impact.

With respect to developing entrepreneurial capabilities, early technology-market matching can first help prioritise markets while the technology is still being developed, modifying the research trajectory within the scientist's laboratory and network, and later allowing the venture to create and capture value based on large, unmet needs. Second, creating reputational signals pre-formation, such as through publishing firm technology specific research in elite journals, and by early patenting, can attract investors and alliance partners as the firm matures and requires additional investment and complementary assets downstream. Third, early mentorship of lab members, such as helping them identify unmet market needs and encouraging them to participate in science commercialisation training programs, builds trust and technical know-how that can accelerate decision cycles and can also prove to be a cost-effective training ground for future senior leaders of the venture, while the technology is still in the lab. Finally, if the venture faces high technology and market uncertainty, incubating the technology in the lab and delaying firm formation until it is closer to commercial viability will better align expected revenue and cash flow timelines with those of potential venture capital investors.

5.6 Implications for policy

Policymakers can support the enrichment of their science innovation ecosystems by facilitating and supporting initiatives that encourage scientist-entrepreneurs to bring their technologies from lab to market. One way to do this is to facilitate the acquisition of pre-formation intangible assets such as international networks and research excellence, by creating and funding research grants that encourage international, interdisciplinary, and translational collaborations. International and market-informed collaboration networks may also be seeded on university campuses through targeted research and innovation events with industry sectors linked to regional and national policy goals. Such events can be particularly useful for early-stage researchers by creating conditions for them to showcase their research and connect with industry. These events can further accelerate the development of international collaboration networks which can then be leveraged through the development of entrepreneurial capabilities.

Policymakers can help develop scientist entrepreneurial capabilities by creating a frictionless environment for claiming and protecting intellectual property, which is currently often constrained by under-resourced university technology licensing offices (Bubela and Caulfield, 2010). Reducing barriers to patenting, and encouraging entrepreneurship activities by scientists, for example, by allowing those activities to partially fulfil teaching, research and service obligations, which has already been suggested by Rasmussen et al. (2020), would align the motivations of policymakers, university leadership and scientist-entrepreneurs. Furthermore, policymakers and university leadership can bridge the gaps within the siloed nature of the academy by creating an environment where academic scientists with little previous exposure to business can develop entrepreneurial capabilities to commercialise their inventions, whether through licensing or spin-off creation. Two ways to accomplish this are by providing funding and support for science faculty and their lab members to undertake science entrepreneurship educational training programs directly related to their lab research, and to encourage and fund interdisciplinary engagement between business schools and science departments. Such support would serve the dual purpose of building the pre-formation intangible assets of international networks, research excellence and patenting.

6 Conclusions

Through examination and analysis of three science-based university spin-offs within the British Columbia biotechnology innovation ecosystem, we find evidence of the importance of pre-formation knowledge-based intangible assets and entrepreneurial capabilities to firm performance, as measured by revenue ten years after firm formation. We contribute to the literature on intangible assets by interrogating a novel science-based context, where its constituent firms are characterised by high technology and market uncertainty, and by developing a model (Figure 1) of the role of pre-formation intangible assets in endowing science-based university spin-offs. This endowment process is enabled by entrepreneurial capabilities, which are critical given the high uncertainty environment under which science-based firms operate. We respond to a call by Schilke et al. (2018) for studies to more fully understand how firm-level dynamic capabilities develop and how the agency of key individual actors may affect firm performance. To the best of our knowledge, our study is among the first to empirically examine and operationalise pre-formation knowledge-based intangible assets and elucidate the role these assets play on the financial performance of science-based ventures. We observe that all three exemplars leveraged pre-formation knowledge-based intangible assets, operationalised through external networks, research excellence, and patenting pre-formation, and the founders of these firms displayed the entrepreneurial capabilities of technology-market matching and mentoring in mobilising these intangible assets. Interestingly, we find only the highest uncertainty firm, AbCellera, displayed the entrepreneurial capability of strategic timing of firm formation suggesting that this capability is particularly relevant in sectors with high levels of technology and market uncertainty.

We provide evidence that entrepreneurial capabilities and intangible assets endow science-based ventures for better chances of success and these capabilities are even more needed for higher levels of uncertainty, such as those found in the biotechnology sector. Larger sums of capital and longer timelines are involved in the commercialisation of these ventures with higher levels of uncertainty. Thus, sound pre-formation decisions on technology-market matching are even more necessary to de-risk and increase their potential for value capture (Maine et al., 2014; Gruber and Tal, 2017). These longer timelines, higher sums of capital, and additional complexity make the seizing capabilities of claiming and protecting the invention, attracting, and mentoring the founding team, and strategic timing even more necessary to create and capture value because of the signalling to and alignment with alliance partners and investors.

In addition to our scholarly contributions, we make recommendations for practitioners and policymakers to more effectively commercialise latent, high potential inventions that are still in the university lab. For example, we find that pre-formation patenting and external networking, when focused through the entrepreneurial capabilities of technology-market matching and claiming and protecting the invention, contributes to firm financial performance. Innovation policy makers and university leadership can strengthen their science innovation ecosystem by facilitating early market prioritisation, strategic patenting, and the purposeful leveraging of a scientist's network. Given the interplay between pre-formation intangible assets and entrepreneurial capabilities for firm success, further support should be provided for educating and mentoring graduate students and postdoctoral fellows as either potential future cofounders of science-based ventures or as more impactful translational researchers.

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