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Amphibious Researchers:
working with laboratory automation
in synthetic biology

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I declare that this thesis has been composed solely by myself and that it has not been submitted, in whole or in part, in any previous application for a degree. Except where stated otherwise by reference or acknowledgment, the work presented is entirely my own.

Signature: 

5 June 2019

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To Katie and Alexander Jack Mellingwood

"such riches …"

Abstract

This thesis analyses the use of robots and automation in academic biosciences laboratories in the UK. Both system vendors and policymakers argue that robots, specifically liquid-handlers and robotic arms, offer more efficient, precise and reliable methods for experimental work. These arguments for the potential of automation systems for the biosciences form a cadre of promissory narratives about the future value of such technologies. One reason vendors promote the use of robots is to remove error-prone humans, with their need for sustenance and sleep, offering instead the mechanical reliability of a robot system unencumbered by such bodily limitations. Somewhat paradoxically, I argue that to negotiate the hybrid disciplinary space of laboratory automation and the biosciences, researchers need significant embodied skills. Furthermore, they must forge relationships among multiple knowledge communities, and engage in boundary-work to manage ambivalences and deal with competing demands. Laboratory-based automation system users learn how to be skilled in embodied 'fingertip-feeling,' and how to be adept at relationship management and boundary-work. To do this, they need to understand both 'wet' cell behaviour and 'dry' robot behaviour; they must become amphibious researchers.

My study identifies five promissory narratives found in policy documents and system vendor descriptions of laboratory automation and the biosciences, particularly in automation-driven synthetic biology. These promissory narratives describe potential future benefits of increasing automation in biosciences laboratories. The five narratives are that automation will: result in more time for researchers because robots are more efficient and more precise; increase parameters and the ability to tackle problems with very large numbers of variables; enhance the reproducibility of experimental results; provide increased technological capacity for laboratories, making them more competitive in international funding arenas; and result in further opportunities for commercialisation of products and services.

Through an analysis of documents, interviews and laboratory practices, I show that these promissory narratives for automation and the biosciences are reconfigured by the lived experiences of laboratory users. I establish that researchers' lived experiences can both challenge and support promissory narratives in this area, and argue that developing understanding of users' practices is essential to an assessment of the future value of automation-driven synthetic biology. My thesis further demonstrates that the ways that researchers make automation systems work in the biosciences involve an attentive engagement between users' bodies, their competences, and their belonging and identity as part of particular groups. Researchers using laboratory automation technologies engage their bodies and manage their relationships to generate trust and confidence in robot functioning. These researchers have to mobilise the 'wet' and the 'dry' simultaneously to maintain a proper functioning system. In short, they must be amphibious researchers.

Lay summary

When scientists conduct experiments in laboratories, they use a range of tools. Research scientists learn how to use their tools and how to work in laboratories in a variety of ways, including through formal training and education programmes and through informal learning. One of the differences between formal and informal learning is that formal learning involves written instructions and informal learning involves learning by doing. In biological science laboratories, researchers use pipettes to mix different liquids and, often, experienced researchers develop their skill in pipetting through practice, and they develop that skill by learning from other researchers and by pipetting themselves. A group of researchers in the field of synthetic biology, and others, have argued that one of the problems of pipetting manually is that human scientists make mistakes and humans cannot pipette accurately and quickly over long periods. One of the solutions that some technology vendors are proposing to this problem is to use more automation in laboratories. Vendors of liquid-handling robots argue that more bioscience laboratories should use automation. Both vendors and policymakers further argue that increasing the use of automation in this field will result in more scientists being able to reproduce results in different laboratories, and to share and collaborate on projects more easily.

My research has analysed these vendor and policymaker arguments and compared them to how current researchers are using automation and robots in their daily work. My findings suggest that current users of automation systems in this area have experiences that help further understanding of what it takes to build a successful automated system in a bioscience laboratory. The time I spent observing and talking to current system-users helped challenge some of the vendor and policymaker arguments and promises about automation technologies. My research demonstrated that there are many different technological solutions currently available for bioscience researchers; however, one of the most important considerations for system builders is not technological in nature. System builders and operators in my study needed to understand computer and biological sciences, and at least some of those researchers needed to feel comfortable working with groups in different academic disciplines. I have called researchers that can work comfortably across academic areas ‘amphibious researchers.’ These researchers are amphibious because they can understand and integrate ‘dry’ computer science laboratory techniques with ‘wet’ biological sciences laboratory techniques. Perhaps most crucially, these researchers are also able to ensure the results they produce using integrated laboratories are acceptable in their respective academic communities. My study therefore recognises that there are different opinions about the usefulness of automation in the laboratory, and that current laboratory users are well placed to judge that usefulness for their particular needs.

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List of acronyms

Term	Description
AAL	Advanced Automation Laboratory
AI	Artificial Intelligence
AL	Assemblers Lab
API	Application Programming Interface
APT	Automatically Programmed Tools
BBSRC	Biotechnology and Biological Sciences Research Council
CEO	Chief Executive Officer
DARPA	Defense Advanced Research Projects Agency

DNA	Deoxyribonucleic acid
DTI	Department for Trade and Industry
EC	European Commission
EMA	Enhanced Microbiology Automation system
EMBL	European Molecular Biology Laboratory
EPSRC	Engineering and Physical Sciences Research Council
ERC	European Research Council
EU	European Union
HTT	High-throughput technologies
iGEM	International Genetically Engineered Machine Competition
ISTC	Intel Science and Technology Centre for Pervasive Computing
IT	Information Technology
KTN	Knowledge Transfer Network
LIMS	Laboratory Information Management System
MIT	Massachusetts Institute of Technology
MSc	Master of Science
N/C	Numerically controlled
OS	Operating System
OT	OpenTrons
PC	Personal Computer
PCR	Polymerase Chain Reaction

PhD	Doctor of Philosophy
PI	Principal Investigator
PM	Project Manager
Q&A	Question and Answer
RAS	Robotics and Autonomous Systems
RBR	Robotics Business Review
RCUK	Research Councils United Kingdom
RL	Rhodes Lab
RQ	Research Question
SBLC	Synthetic Biology Leadership Council
SSK	Sociology of Scientific Knowledge
STS	Science and Technology Studies
TSB	Technology Strategy Board
UI	User Interface
UK	United Kingdom
US	United States of America
USB	Universal Serial Bus
VAT	Value-added Tax

CHAPTER 1:

Introduction to the thesis

In this thesis, I argue that a properly functioning automation system in bioscience laboratories requires amphibious working knowledge. The root of the word amphibian, 'amphibios', is Greek, and translates as 'living a double life.' To be both land- and water- based shapes every aspect of the life cycle for an amphibian, and to understand behaviour in one habitat necessarily requires understanding of how an amphibian lives in the alternative environment. For builders and operators of automation systems in the bioscience laboratory there is a similar mirroring, a doubling-up that has to be maintained to keep their systems functioning across wet and dry laboratory spaces. I call these users 'amphibious researchers' and the knowledge they develop through training and practice 'amphibious working knowledge'. Specific groups of users of automation determine what constitutes proper functioning of automation systems, and it is their amphibious working knowledge that enables them to make these judgements. The empirical work of this thesis has been dedicated to what proper functioning looks like for users of laboratory automation systems in the academic biosciences in the UK.

This introduction to the thesis outlines the overarching argument that I am making about automation in the biosciences. In brief, I have identified a set of researchers in bioscience laboratories that must negotiate both 'wet' biological and 'dry' robotics knowledge communities. These 'amphibious researchers' use their training and develop a 'fingertip-feeling' for both cell and robot behaviour: in short, they are practitioners of 'amphibious working knowledge.' Amphibious researchers designing new large-scale DNA assembly centres are also amphibious for another reason. These new system builders must negotiate several different communities in both academic and industrial organisations. For these new system builders, amphibiousness involves 'living a double life' because, alongside negotiating the working knowledge needed to create a successfully functioning automation system, these builders and operators must also negotiate multiple professional and disciplinary identities. These amphibious researchers must be both academics and engineers, and both researchers and service providers with a customer focus. The practice of amphibious working knowledge,

therefore, also raises questions around what it is to be an academic in the biosciences when policy makers, vendors, and researchers plan and act for a more automated future. Rather than attend either only to the laboratory or to policymaking and discourse, my research methods sought to span these domains, to understand better, when policy and practice are or are not related or influencing one another.

To appreciate how I formulated this overarching argument I begin with a discussion of some of the historical links between molecular biology and computer science, specifically in relation to automation and synthetic biology. I then examine the theme of promises and discuss the relationship between automation technologies, promissory narratives, and futures. The remainder of the chapter outlines the structure of the thesis and my overall research aims for the study.

1.1 Why automation and synthetic biology?

Some policy makers and researchers see automation as a solution for current challenges in the biosciences (discussed further in Chapter 4). The problems of understanding biological complexity have a longer history. From the early twentieth century, scientists have explicitly sought to understand and control living systems at a molecular level. Kay (1993) discusses the period 1920s-1950s when researchers began to practise biology at the molecular scale. This agenda for understanding biology through its constituent molecular parts, in Kay's narrative, was pushed forward by American scientists and their patrons as they ushered in a 'molecular vision of life' (Kay 1993: 3). Genetic engineering, as a term, was introduced by writers in the 1930s (Prasad 2008), with the creation of new organisms, and the term returned to prominence with recombinant deoxyribonucleic acid (DNA) technologies in the 1970s (Campos 2010). Researchers began using the term 'synthetic biology' in the early 2000s and defined this new field as the systematic application of engineering knowledge and technologies to biological sciences (Endy 2005, Heinemann and Panke 2006, O'Malley et al. 2008).

The proffered benefits of engineering expertise for biology are for more precise experiments, on a larger scale, with greater efficiency, and to foster activities in standardisation across biological engineering. Standardisation is needed, according to

some researchers in synthetic biology (e.g. Kitney and Freemont 2012), for necessary advances and innovations in expertise and technology to take place. Therefore researchers are calling for a coordination of research and increased productivity in biological engineering (Endy 2005), and increased instrumentalisation of biology as a technology for meeting a wide range of present and future societal needs. Synthetic biology, as portrayed in UK government policy accounts, has the potential to 'heal, feed, and fuel us.' (Willets 2013: 10)

One solution for standardising certain procedures in the laboratory, pursued by some advocates of biological engineering, is to increase automation in the laboratory. In different disciplines, including the social sciences (Bruce and Yearley 2006) and management consultancy (Sadler 2001), automation is a highly topical issue. Often, in weblogs and articles (e.g. Ford 2015) writers link the rise of automation to technological developments pursued by companies based in California's Silicon Valley in the United States. A current example in media reporting about automation is Google's autonomous vehicle project. According to Adams (2015), a journalist who spent time interviewing Google employees and senior staff, Google's self-driving car is poised to change society in fundamental ways, particularly in reducing car-related deaths by improving road safety. Looking at self-driving cars from a UK perspective, the government has invested in a £10 million fund for research into 'how driverless cars can be integrated into everyday life in the UK' (Perry 2014). Clearly, companies and government bodies have placed significant interest and investment in to automation research, and, as I go on to demonstrate below (particularly in Chapter 4), researchers in synthetic biology are also looking to automation research as a potential source for advancing the biosciences.

Autonomous or self-driving cars incorporate mechanical propulsion, environmental sensors, and computer-derived algorithmic decision-making. That is, self-driving cars aim to replicate some actions currently taken by human drivers and to replace the way those actions are taken with a set of sensors and software programs. The engineering knowledge and expertise needed to create the autonomous car is already in use in manufacturing and service industries. For example, Amazon has introduced automated robotics technology into ten of their US warehouses. These robots, named Kiva, are

designed to automatically select and retrieve shelves of goods and bring them to employees to pick and pack orders (Frizzel 2014). Looking ahead, the management consultancy firm McKinsey predicts that autonomous systems will replace, to a large extent, the traditionally 'white-collar' tasks of knowledge-work over the coming years. Knowledge work liable for automation, as defined in the McKinsey report, is any task that involves aspects of systematic counting, classifying and recording, and extends from traditional financial management and accountancy to professions including medicine and law. The McKinsey report authors extrapolate significant future economic impacts from this automation of knowledge-work, ranging from $5 – 7 trillion by 2025 (Manyika et al. 2013).

The numerous articles and government reports into automation suggest that a diverse range of vendors and users are now interested in the field. With such a major societal focus on automation then, why have I chosen to focus attention on automation in the laboratory? I contend in this thesis that there is a concerted effort to prove the value of automation for the biosciences, which is not widely held, understood, or shared by laboratory users. I show that the lived experiences of laboratory users reconfigure many of the promissory narratives that vendors and policy makers put forward for automation at large, and the potential benefits that more automation will bring. Ultimately, I chose to focus the thesis on the biosciences – particularly synthetic biology – because there is a congruence between the promises made for synthetic biology's future and the promises made for automation's future; indeed, in some cases policy makers contend that the future of the two areas is inextricably linked.

1.2 Technology and the future

I have identified the role of amphibious working knowledge in the proper functioning of automation in the biosciences. Part of users' assessments of proper functioning involves judgements about the 'right' result, and the 'right' technology to get that result. Often, in my data, user speculation about the right technology for a particular task was intimately bound up with how well the experimental results (data outputs) matched user expectations. Furthermore, users' confidence in their automated systems ebbed and flowed in relation to the tests they performed based on existing knowledge of good laboratory practice and through user collaboration with other experts. For

example, users often shared results with researchers in their project group and discussed the validity of those results. Researchers would use a combination of published findings on the expected behaviour of the cell in question, discussions with colleagues, and knowledge about the way the automation system had performed to demonstrate why the results achieved were good or bad. Researchers in my study rarely spoke of the future in terms of ever-increasing automation in their work.

However, seen from a policy perspective, depictions of automation in the biosciences are full of promises for what these technologies will do for progressing the biosciences, particularly by removing routine and mundane aspects of bioscientists' practice. These depictions are promissory in their portrayal of a future that is improved by automation. These promissory narratives portray developments in automation technology as rapidly advancing and the reaction times of the UK academic biosciences community as problematically slow. In these framings, the promissory narratives about automation for the biosciences are implicitly technologically determinist. That is, these narratives imagine automation developing as if under its own momentum, and conclude that the UK academic community needs to adapt to these changes, particularly to promote economic growth and research competitiveness for the nation.

It is important to note that not all of the narratives I identified about automation contained promises. Indeed, some of the practitioner narratives I analysed contained significant doubts about the potential benefits that automation will bring for laboratory work in the biosciences. Indeed, part of my aim in this thesis is to demonstrate how the promissory narratives about laboratory automation do not always correspond to the lived experiences of practitioners. Often the doubts about automation in my analyses were found behind closed doors, or in passing conversations between researchers using automation systems in their work. The narratives that were sustained in public representations of automation for the biosciences were predominantly promissory: they contained implicit and explicit reference to the changes that automation was going to bring to the academic biosciences. As my empirical data shows, often the same informants in my study went back and forth between positions of promise and positions of doubt in relation to their systems. In either case, however, I witnessed the

importance of amphibious working knowledge for keeping the system functioning correctly.

The definition of a narrative as a linking together of 'events into a sequence that is consequential for later action' (Riessman 2008: 3) is a useful way for me to think about automation as I find it in the academic biosciences in the UK. Indeed, as I explain in Chapter 3, Research design and methodology, I used ethnographic vignettes and interview transcripts to generate many of the insights that underpin the central argument of this thesis. Narratives about automation can be promissory because they stand out, through repetition or longevity, or because the story is curious in some other way; for example if it conflicts with another story in interesting ways. Several of the most common promissory narratives I found about automation support the idea that increased automation brings increased control, precision, and efficiency. The methodological choices I made to use ethnographic fieldwork and follow-up interviews came in part from a recognition that policy narratives about automation had the potential to influence choices around automation procurement, and that user experiences should form part of that decision-making process. My aim in using ethnography was to add users' narratives to the discussion and to show how those users' lived experiences challenged or supported promissory narratives about automation for the biosciences.

1.3 Research aims

My overall research aims were to understand the ways in which promissory narratives of laboratory automation for the biosciences, particularly synthetic biology, were being challenged or supported by users' experiences. To adequately understand those user experiences, I also aimed to explore how users gained trust and confidence in their own methods and practices and how those practices influenced users' explanations of their place within their chosen fields. Finally, understanding user experiences and identities also necessitated finding out, in some detail, what actions users actually took to create and maintain successful systems.

As I go on to describe below, insights from social shaping of technology literature demonstrate that 'the fact that machines " work" [is] something to be explained rather

than taken for granted' (MacKenzie and Wajcman 1999: 22). Furthermore, when policymakers and vendors make predictions about a technology's future value they are also contributing to the future direction that technology will take (Michael 2000). In synthetic biology particularly, which is a field marked out by its practitioners as one with significant potential, exercises by STS researchers (e.g. Frow and Calvert 2013b) have engaged those practitioners to imagine futures not routinely seen in policy accounts, and found that alternative and unexpected futures do emerge by engaging directly with practitioners. By observing the practices of laboratory automation researchers, I set out to answer my main research question: In what ways do the lived experiences of laboratory users support or challenge the promissory narratives of laboratory automation for the biosciences? (RQ1). Observing and listening to researchers allowed me to explore how policy and vendor speculation about the future value of automation may be reconfigured by the local conditions and lived experiences of laboratory users.

To understand the local conditions of different laboratory users it was necessary for me to find out how those users gained trust and confidence in the available methods for experimental work in their fields. Existing work in STS and synthetic biology has already shown the links between methodological choices and debates about identity; indeed disputes about the right methods for conducting 'real' synthetic biology often stand as proxies for debates about professional and disciplinary identity (Schyfter 2013). I therefore aimed to understand how laboratory users engaged in forms of 'boundary work' (Gieryn 1983) to distinguish their own and others' work as being part of the 'real' work of developing laboratory automation for the biosciences (see RQ2, below). Gieryn's (1983) examples show boundary work in relation to the demarcation of science from non-science. Boundary work, briefly, is an active process of delineating a set of practices or actions by setting out differences between those practices and other seemingly similar practices. I aimed to understand the ways in which laboratory automation researchers were engaged in rhetorical work of exclusion and inclusion (Gieryn 1995), and to use these insights to illuminate what it means to be a biosciences academic. These questions were particularly salient for academic

researchers who were responsible for the success of multi-million pound investments in automation systems.

Finally, one of the underpinning policy and vendor narratives about laboratory automation is that liquid-handling robots can replicate existing actions taken by researchers using hand-held pipettes. Moreover, these promissory narratives state that robots will complete those same tasks more effectively by: saving researchers' time; increasing reproducibility of experiments; allowing researchers to conduct larger and more complex experiments; increasing research institute capacity for grant income generation; and enabling more commercialisation opportunities for researchers. As well as being promises for the future value of automation systems, these narratives suggest machines as solutions to overcome the bodily limitations of humans. However, as I go on to outline in this thesis, the bodies of researchers are bound-up with the successful functioning of the systems that researchers operate: laboratory users develop a 'fingertip-feeling' (MacKenzie 1999: 426) for ensuring the successful practice of wet and dry laboratory work. A further research aim for my study was therefore understanding what successful replication of human actions by a liquid-handling robot looks like for current laboratory users (RQ3).

1.3.1 Primary research question

RQ1: In what ways do the lived experiences of laboratory users support or challenge the promissory narratives of laboratory automation for the biosciences?

1.3.2 Secondary research question(s)

RQ2: What forms of boundary-work do laboratory users engage in when explaining the work of laboratory automation?

RQ3: What does successful replication of human actions by a liquid handling robot look like for current laboratory users?

1.4 Structure of the thesis

To demonstrate how I used my empirical work to generate the argument outlined above I have organised the thesis in to eight chapters. In Chapter 2 I review several theories that help to show that technology adoption is a historically and socially contingent process. For example, scholars writing about the social shaping of technology (e.g. Edge 1988, Mackay and Gillespie 1992, Williams and Edge 1996, MacKenzie and Wajcman 1999) have provided numerous case studies detailing how the social context fundamentally affects how a technology develops. Insights such as this, from the field of Science and Technology Studies (STS), help to show that social context fundamentally affects technological trajectories; that is, the way a technology is designed, developed, and used over time. In Chapter 2 I further outline theories from the sociology of expectations literature (Van Lente 1993, Borup et al. 2006) to help explore some of the rhetorical work that goes on when promises about automation and the biosciences are made salient by different groups. The rhetorical work of making predictions about technologies, identified by the above authors, helps to demonstrate that making predictions about the future of a technology is not idle speculation; future expectations legitimise actions in the present (Brown and Michael 2003, Frow and Calvert 2013b).

Automation often involves, as with the self-driving car example above, an element of using sensors and computer programmes to complete a task previously completed by a person. Programming a machine to complete a task often requires identifying many individual actions and writing out explicit instructions for how the machine will complete those actions. Making actions explicit in this way simultaneously raises questions about many of the implicit actions that also form part of the completion of a task. To explore these issues Chapter 2 also reviews theories of 'tacit knowledge.' There is no single definition of tacit knowledge, but scholars inspired by Polanyi (1958) and others, have been interested in skills or understandings of phenomena highly dependent on 'how-to' knowledge, often most significant in cases where mere communication in writing or by other means would be insufficient, and instead one must learn by doing. I complete the chapter with a discussion of the way that the life sciences have been conceived of as a set of embodied practices (Myers 2015). The

chapter ends with an explanation of how Mackenzie's (1999) version of tacit knowledge, as a form of bodily 'fingertip-feeling,' was most useful for understanding practices of amphibious working knowledge as I found them in the automation of synthetic biology and the biosciences.

Chapter 3 explains the research design and methodology I used to conduct this study. I attended a series of events and conducted pilot work to help shape the research design. My aim was to use research methods that best captured the ambiguities I began to encounter when observing efforts to automate bioscience laboratories. I was interested in how the promises and narratives about this area were constructed in written policy documents and government reports. I was particularly interested in how these policy narratives fitted with the lived experiences of current laboratory users trying to implement automation systems. As well as formal semi-structured interviews, it was necessary for me to use ethnographic methods to observe practices and illuminate what was being done in these laboratories as well as what was being said about how automation was changing these same users' lives for the better.

The 'facet methodology' approach (Mason 2011) was very useful for capturing the differing perspectives on automation for the biosciences from a range of angles. Facet methodology, briefly, is the approach that allows for multiple streams of data and data collection methods, and promotes consideration of seemingly disparate data points to allow researchers to identify the overall object of concern. The term 'facet' is used metaphorically to explain how the research process can turn on unexpected and seemingly minor insights.

The theme of promissory narratives is further unpacked in Chapter 4 where I review a selection of the policy documents and grey literature that have been published about automation and the biosciences in the recent past. The content of this grey literature search includes several examples of issues in the biosciences that could potentially be solved by increasing automation in the laboratory. I also use Chapter 4 to look at a number of alternative solutions to issues in the biosciences that companies and laboratories are considering, particularly solutions that do not involve any significant need for automation in the laboratory.

In Chapter 5 I follow those promissory narratives found in policy documents and compare them as they are taken up, challenged and reframed by practitioners at a series of workshops and conferences. The initial pilot empirical work explored in Chapter 5 was pivotal in my choice for selecting automation for the biosciences as my research object. As that chapter highlights, practitioners in synthetic biology and the biosciences do not have a shared consensus on the future of their related fields when considering automation systems.

The main empirical work from the study is analysed in Chapters 6 and 7. These two empirical chapters describe and evaluate data collected at two different academic laboratories in the UK. The first case study site, the Rhodes Lab[1] (RL) is an academic biosciences laboratory with a long history of developing automation systems. The laboratory Principal Investigator (PI), Kieran, had been developing techniques to automate experimental work for over ten years at two different institutions and had experienced several funding rounds, multiple funding body sponsorships, and changing research agendas. The second case study site, Assemblers Lab (AL) is a recently launched DNA assembly centre, funded through large capital infrastructure investments by Research Councils UK (RCUK). The AL was initially conceived and developed by one academic laboratory and has several commercial partnerships with international software and hardware providers. The long-term goal for the AL is for the service to generate sufficient commercial income as a fully automated DNA synthesis[2] provider, and to maintain financial viability after research council funding no longer covers the costs of the centre.

I conducted 18 months of ethnographic observations, at my two different sites, which involved numerous informal interviews and discussions. I also completed 15 in-depth formal semi-structured interviews, and collected multiple documents for analysis

[1] 'The Rhodes Lab' is a pseudonym. All names used throughout the thesis are pseudonyms. This includes the naming of individuals and naming organisations, and follows the agreed ethical requirements for anonymization (see Appendix 2 for a copy of the ethical documentation).

[2]There are several large DNA synthesis providers internationally, including Gen-9 and Transcriptic. Such services offer biosciences researchers a way to out-source the work required to build, or 'synthesise' a specific set of DNA molecules according to the needs of individual researchers. The Assemblers Lab team aimed to enter this market place by offering bespoke DNA design and synthesis services to researchers, especially targeting the need for unusual or large DNA fragment synthesis.

across these two case study sites. The core data used for analysis at the Rhodes Lab in Chapter 6 and the Assemblers Lab detailed in Chapter 7 was ethnographic observations and some semi-structured interviewing. I also visited, emailed, and interviewed a number of informants not based within the two case study sites. I encountered these additional informants at events that happened during my time at each case study site and the discussions that took place acted as supplementary material for understanding my findings at each site.

In Chapter 8 I bring together the analysis from the preceding chapters and make a case for recognising the necessity for amphibious working knowledge in a successfully functioning automated system in the academic biosciences. The focus of my research, in short, is on the practices of laboratory users engaged in using automation for their experimental work, particularly inside settings replete with promises and anticipations for automation. In this thesis, I propose that robots and automation, in the biosciences at least and in current form, are becoming tangled up in the day-to-day lived experiences of a number of laboratory users. However, I argue that these lived experiences necessarily reconfigure the prominent narratives for laboratory automation and synthetic biology through the local conditions at each of my sites.

1.5 Conclusion

In this chapter I have set out the choices I have made during the course of my research. These choices have included my focus on laboratory automation for the biosciences, particularly synthetic biology. I have described why automation and synthetic biology were pertinent research objects for my study, and the methods I have chosen to investigate those objects. My discussions in this chapter have also introduced five key policy-maker and system vendor promissory narratives about automation and synthetic biology, and why research that analyses promissory narratives has helped me to identify and pursue the questions addressed in this study. Moreover, these research aims are laid out in this chapter with reference to theories in three areas, namely: narratives of technology and the sociology of expectations; identity, trust in methods and boundary work; and tacit knowledge as a form of 'fingertip-feeling.' I have also

outlined how these research aims are addressed in the thesis structure. The next chapter reviews a number of relevant theories and ideas from STS literature, including the three outlined above, to further contextualise the main findings from my study.

CHAPTER 2:

Contextualising narratives of technology: theories of promises, identities, and tacit knowledge

2.1 Introduction

At the outset I was motivated by the observation that most recent policy and media stories about automation in the biosciences contained an implicit technological determinism. One of the aims of this chapter is to review literature that questions the naturalness of technological progress. I noticed early on in the project that automation required significant embodied skill from human operators, at the same time as automation advocates proposed automation as a solution to the problem of human-error and inefficiency in biological science. I therefore on the one hand needed to better understand automation and its practices, as understood most broadly, and also literature on embodied practices, which might matter for biology particularly. In the following three sections, I introduce literature on expectations, identities, and tacit knowledge. The chapter culminates in a fourth and final section introducing an idea central to the overall thesis, that of 'fingertip-feeling.' I draw on this literature to understand automation as a set of technological choices that groups must negotiate according to user needs and preferences. I use these sets of literature to argue that user choices about the right method and the right tools are also issues of identity and of embodied knowledge.

I start by reviewing literature that examines the future value of technologies. For example, in the area of the sociology of expectations (Van Lente 1993, Borup et al. 2006) authors provide case studies of speculations about technologies. In these case studies, the authors show that talking about the potential future value of a technology is not idle speculation; rather, making predictions about technological futures helps to legitimise actions in the present (Brown and Michael 2003, Frow and Calvert 2013b). I examine these ideas with automation and the biosciences in mind, particularly because the future technological trajectories for the biosciences seem far from certain, as Chapters 4 and 5 help to demonstrate.

Debates about the level of automation needed for future experimental work include discussions about the right methods and tools to use in a laboratory. Therefore, this chapter also explores the links between tools and identity, and introduces the concept of boundary-work (Gieryn 1983, Gieryn 1995). Gieryn's concepts help to illuminate the rhetorical work of inclusion and exclusion in the demarcation of science from non-science. I also apply Gieryn's arguments to the demarcation of the correct tools from incorrect tools in the biosciences, and explore different understandings of what identity means and how identity is about affiliations and choices. In the context of synthetic biology, authors have already demonstrated that debates about the correct methods and tools also stand as proxies for debates about identity (Schyfter 2013). As we will see in the following chapters, there are many potential tools available for bioscience researchers in the laboratory and many of those tools offer different solutions to the same problems. I explore how these differences might manifest in questions of disciplinary identity, specifically what it means to be a practising academic biosciences researcher who uses automation tools, and how evolving expertise in the use of different tools helps researchers to progress in their careers.

When users encounter multiple solutions to the same problems in academic biosciences research, they also debate the strengths and weaknesses of those solutions. Among the five promissory narratives outlined in the last chapter, a common identifying theme was that automation solutions promise to help users to overcome limitations of their own bodies. For example, one person could not continually pipette solutions in an experiment that required modifications every hour for a 24-hour period without sleep deprivation affecting that person's practice. Automation advocates argue that robot systems can perform some of the same tasks as researchers without the issue of bodily limitations risking the quality of that practice. Accordingly this chapter examines literature concerned with understanding how bodies are implicated in different areas of scientific practice, specifically exploring the life sciences as a set of embodied practices (Myers 2015). Moreover, the final part of the chapter examines theories of how automation advocates understand the work involved in using computers to complete tasks previously completed by human operators. I focus on theories of tacit knowledge (Collins 1990, MacKenzie and Spinardi 1995, Collins and

Kusch 1999, MacKenzie 1999, Collins 2010) to explain human action and technology use.

2.2 Aims of the chapter

It has been several decades now since social scientists put forward a sociology of technology that demonstrated how technologies do not simply develop as if by natural laws. Technologies do not just impact upon a passive society that can either adapt to the changes being wrought or reject those technologies altogether. A more accurate analysis of technology, both politically and intellectually, is to view technological artefacts as socially shaped, not just in their applications and uses but also in the design and technical content of those artefacts. To propose that automation technologies in the biosciences are socially shaped is not sufficient. A major benefit of the social shaping approach is to show *how* particular technological developments are shaped: the power of the analysis 'lies in the details' (MacKenzie and Wajcman 1999: 9). With reference to understanding automation for the biosciences, one of the aims of this chapter is to show how expectations, identities and users' bodies each contribute to the development of automation platforms.

2.3 Structure of the chapter

To meet the aims above I have organised this chapter into four over-lapping sections. I begin by briefly examining some past research looking at using automation to try to improve industrial production and factory practices. I present speculations about what automation will do for productivity and factory workers as analysed by scholars in the late-twentieth century. I further explore how the sociology of expectations literature can help to demonstrate that speculations made in the past were situated in a particular period; one aim of this chapter is to understand what still remains of those promises in more recent expectations for automation in the biosciences. The next section of the chapter further unpacks the notion that questions about the correct tool and method are also questions about identity and belonging in the biosciences. That is, what one chooses to do, and how they do things, is also part of how a person sees themselves in relation to others. The third and fourth parts of the chapter consider theories of tacit

knowledge and embodied knowledge. I consider how these theories intersect, with a particular focus on molecular biology, teaching and learning, and using machines to mimic the actions of human operators.

2.4 Future value and expectations for laboratory automation technologies

> ‘Future visions have enormously powerful consequences for society, carrying with them implicit ideas about … the common good.’ (Wajcman 2017: 125)

Promises made about the future value of a technology are not just speculation, promises legitimate actions in the present (Frow and Calvert 2013b). For example, Urry (2016) contrasts the utopian technological visions and ‘global optimism’ (p.29) of the 1990s, to the plethora of bleak dystopian technological visions in the early 2000s, which he labels the ‘new catastrophism.’ (p.135). Huge public and private investments in emerging digital technologies in the 1990s were predicated upon a utopian vision of a borderless future global economy. In this vision, the West had won the Cold War and digital technologies were an essential component of a future based on global consumerism. From around 2003 onwards however, Urry lists the plethora of books, films and research programmes dedicated to an imagined collapse of human society. In these visions, the utopian optimism of the roaring nineties has been swept away and replaced by a new catastrophism, a future of environmental collapse and species extinction. Such a bleak dystopian vision of the future, for Urry, helps to explain investments in different research and policy areas, including research centres focused on the topic of risk, and government policies concerning non-fossil fuel energy sources. These insights matter for automation and the biosciences because they show the relationship between future speculation and research practices can shift dramatically over time. As I explain in Chapters 4 and 5, current researchers articulate varying levels of faith in the power of automation for the biosciences, and at times they hold competing future visions.

The sociology of expectations literature looks at how expectations for technologies shape their development. This literature highlights that future expectations about established and newly-emergent technologies are often presented and represented

differently at various points during a technology's development (Brown and Michael 2003). Importantly, expectations about the future value of a technology are always 'situated' because particular framings for the potential of a technology are linked to the contexts and circumstances of the groups speculating about these technologies.

To help illustrate this point I now analyse how different scholars have described the adoption of automation technologies. Several scholars have examined what happens in workspaces as governments and companies invest in automated technologies. For example, Blauner (1964) identifies four stages in the development of the factory system: craft, machine tending, assembly line, and automated technologies. Blauner sees the factory system as a movement from types of artisanal working to mechanised non-human production. It is interesting to see how Blauner imagines craft and care (what he calls 'tending') as being stripped away as the factory system is increasingly based on automated technologies. This is a particular vision of automation situated in the 1960s United States.

Blauner also considers the relationship between worker alienation and freedom and the social organisation of factories. Blauner draws on Marx and Weber in viewing alienation as an experience of lack of control and freedom in the work space because of the separation of ownership and the worker (Turner 2009). In his empirical study, however, Blauner finds a weak link between automation and alienation for workers in the chemical plant industry. Blauner derives his optimism for automation from his observation that the workers gain a high degree of responsibility for non-manual tasks (Peterson 1965); in this account the workers experience freedom through increased technological skill. Said differently, this might be a technological expectation that automation will not replace and alienate human workers but will instead allow factory workers to derive more freedom in their work by providing new sets of skills.

In contrast to Blauner's focus on technological skill as a source of freedom, Braverman (1999) proposes an analysis of technology in which skilled worker tasks are mechanised leading to disenfranchised workers and increased control for the owners of factories:

> The capacity of humans to control the labor process through machinery is seized upon by management from the beginning of capitalism as the *prime means whereby production may be controlled not by the direct producer but by the owners and representatives of capital*. (Braverman 1999:158-159, emphasis in original).

For Braverman the technological expectation for increasing automation in factories is that workers will be deskilled and disenfranchised, thereby ceding more control to managers and factory owners. Noble (1999) highlights that numerically controlled (n/c) machine tools, developed with US. Air Force support after the Second World War, relocated the knowledge needed for production away from skilled machinists. Massachusetts Institute of Technology (MIT) graduate engineers, hired to write programs for automating the machinery, aimed to improve production efficiency and reduce human error. Ongoing US. military support was required to keep the project going, however, because MIT engineers experienced significant difficulties in synthesising the skills of experienced machinists. Here we can see that a technological expectation that n/c machine tools would reduce the need for skilled machinists was not so straightforward. The engineers battled to create the software to control the machine tools reliably and it took further US. military investment to create a system flexible enough to maintain the economic viability of the entire project of n/c production. Parts manufacturers eventually stopped employing MIT graduate students to prepare program controls manually and, in 1956, the US. Air Force pushed for a new system called Automatically Programmed Tools (APT). As a flexible systematised solution, APT was a skeleton programme that was not designed to produce one particular machine part but rather as a set of instructions for moving a cutting tool through space. Again, the expectation for the power of n/c machine tools shifted from needing manual programming by graduates to having a library of automated machine movements that could be utilised for making multiple machine parts.

For automation in biosciences laboratories, explored in detail in Chapters 6 and 7, these insights demonstrate that creating machines that mimic the skills of human operators requires attention not only to the capacities of humans and machines, but

also to the capacity of machine vendors and operators to remain flexible enough in their approach to respond to the changing needs of their investors over time.

As the Noble case study demonstrates, companies developed automation technologies in response to the needs and priorities of government, in this instance the US. Air Force. At this point in time the US Air Force promoted a technological vision of fully automated n/c production that would remove the need for error-prone machine part operators. These expectations helped to shape the development of the n/c system and, initially at least, those expectations appeared to be correct. However, rather than simply replacing the skilled machinists that came before, the automated machine tool technologies needed continued funding and development because MIT engineers struggled to replicate the actions of the machinists. More than this, those same machinists provided the constant benchmark of acceptable quality as manufacturers reorganised and retooled in response to the changing demands of the US. Military. The APT system appears exemplary in this context as a technology that had expectations shaped, maintained and recast according to the changing social and political milieu at that particular time and place. Noble's case study matters in the present chapter because he shows that replacing skilful operators with automated processes is not simply a question of the effective programming of machines; for the APT system to be judged successful, communities of skilful and authoritative vendors and operators had to demonstrate that system's value to the main investor, the US. Military.

In the academic biosciences, judgements of success and attributions of authority in laboratory automation development remain tentative, as Chapters 4 and 5 below demonstrate.

2.4.1 Critically evaluating promises: the example of 'knowledge engineering'

A further way to think about what is happening when humans work with machines that aim to mimic human action, is through the idea of knowledge engineering. In computer science, a number of experts in programming and systems development have been attempting to create programmes to conduct knowledge acquisition. These knowledge engineers are concerned with how to codify and transfer knowledge. One of the principles of knowledge engineering is that one day computers will replace humans

completely in some tasks, by creating expert systems that codify the knowledge of human experts for utilisation by machines. This principle contains a particular conception of what knowledge is: something that is stable and can be extracted, abstracted and codified from the minds of human experts. Forsythe argues that this conception of 'knowledge acquisition' is problematic (Forsythe 1993). As I have experienced it, the system builders at my case study sites are not so much interested in the machine performing the tasks in exactly the same way, as a human would do. Moreover, they are less interested in codifying the 'how' of the tasks they complete as they are in understanding 'why' the results that come out of the machine may be similar or different to the results they were expecting.

Forsythe discusses personal and intellectual styles of 'knowledge engineers'. A personal style might be being introverted, for example preferring computers to humans. An intellectual style refers to 'reification' of knowledge; that is, the way knowledge engineers draw a distinction between 'expertise' and 'common sense'. Forsythe's knowledge engineers believe expertise should be codified and (generally), for a proper understanding of knowledge acquisition common sense should be ignored. Importantly, 'common sense' is not viewed as knowledge by her informants, and when they reason about intelligence, her informants use 'I am the world' reasoning. That is, when hearing a statement that applies to them, they take it to be generally applicable, rather than seeking empirical evidence to verify intuitions they use introspection. Forsythe argues that the processes of 'knowledge engineering' requires the deletion of the social and cultural situatedness of knowledge. Apart from the problems this kind of knowledge engineering approach has for the knowledge engineers themselves, the wider implications are that expert systems will implicitly contain the values and perspectives of a narrow group mirroring the cultural and social characteristics of the system builders and the limited number of experts they consult.

Forsythe's knowledge engineers aim to record and codify expertise to preserve valuable knowledge currently practiced by skilled human workers, through knowledge acquisition in computer programs. As Forsythe argues, however, many different types of knowledge contribute to expert understanding; therefore, acquisition of knowledge by computer programs is always partial in her case studies. These insights matter in

later chapters (5, 6, and 7) because researchers using automation systems recognise that robots only provide part of the answer when considering using automation to mimic the skills of human operators. In the next sections, I further unpack these notions of knowledge types with reference to disciplinary affiliations and identity.

2.5 Identity and methods: choosing tools and aligning with disciplinary groups

> 'How do we become passionately attached to particular ideas about who we are; about right and wrong; about good and bad; competent and incompetent?' (Petersen 2013: 55-56)

It is possible to use both theories of boundary definitions and theories of child development to unpack the complex relationships between identity, technology and learning to be skilful and competent. I have explored identity in automation-driven synthetic biology using concepts of boundary-work (Gieryn 1983, Gieryn 1995) and how scientists and others have demarcated science from non-science. I subsequently considered boundaries using Judith Butler's exploration of Foucault's ideas on identity, to understand identity-formation as having 'passionate attachments' to others (Butler 1997). For both boundaries and attachments, I see that understanding who a person is as an individual is also a process of understanding who that person says they are not. Similarly, understanding who a person is, is also understanding what a person does. These insights matter for my research because informants at my sites (see Chapters 6 and 7) repeatedly discussed their roles as something different to what was happening in other places, and used these particular skills and experiences to express their value and place as part of their respective teams, and to indicate future career ambitions.

Petersen (2013) applies Butler's passionate attachments to the experience of becoming an academic. Petersen explores how becoming an academic is about sustaining a performance of 'academicity' (Petersen 2007). This performance is about the continued re-achievement of 'recognition as … legitimate and relevant … in the academic context' (Petersen 2013: 62). She might have a title, a name plaque on her door, and an office but it takes the legitimisation from other academics to be an academic. It is what she does in her writing and her talking, and how she uses her tools

of writing and publication, teaching and presentations that enable that identity to sustain. I take these ideas forward, particularly in Chapter 7, to show how user selection of appropriate tools relates to how that user identifies with certain characteristics of their chosen field.

Passionate attachment is the concept that children form a sense of self, a sense of who they are, at the same time as they depend upon others (usually their parents) for survival. Children must be passionately attached to their caregivers in order to survive, and those relationships form part of a child's development and sense of identity. Importantly, for Butler, because children must rely upon others for survival, and those others are in a position of dominance and control, a child's 'attachment … is produced through workings of power.' (Butler 1997: 6)

Passionate attachments to the right method and good results are also deeply implicated in questions of competence and skill. I see a complementarity between Butler's passionate attachments and Ingold's (1997) 'attentive engagement.' Briefly, Ingold posits that learning to become skilled in a particular task has deeper importance than the end-goal of completing that task. When people learn how to become skilled, they learn how to be attentively engaged with objects in the world, and, through this learning to become attentively engaged, groups of people also learn how to be in the world; they learn, in short, who they are. Linking these insights with Butler's theories, we can see that attentiveness to things and attachments to people must be negotiated through workings of power. Just as children rely upon caregivers for survival, novices also rely upon experts to learn how to become skilled and competent members of the group. In this way, experts are in a position of dominance in relation to novices, and therefore novices are subject to the norms and rules of their expert tutors. In later chapters, I further develop these ideas in relation to becoming an amphibious researcher.

I see definite links here with Tim Ingold's writings on the anthropology of technology. Ingold (1997) uses examples from his observations of knot-making to propose that learning how to become skilled is a process of 'attentive engagement' between a person, the learner, other persons, teachers, and objects and tools. To become skilled

at knot-making for creating fishing nets for example, requires an attentive engagement between the net makers' hands and fingers, and their ropes and strings. This process involves attentive engagement to how seasoned net-makers tie their knots and it involves learning how to be attentive, and what deserves attention in making good fishing nets. Good net-makers aim to catch more fish with their nets but the process of net-making has deeper meaning than this; learning how to make nets has its own intrinsic intentionality because skilfulness in net-making, like academicity, forms part of the identity and belonging that each group member experiences through their learning.

In terms of what deserves attention in the process of making an artefact, this can come down to a question of emphasis. That is, different group members may choose to emphasise different aspects of the net making process (in Ingold's example, above) depending on each person's particular background and interests. This point becomes more salient if members of different groups attempt to work together and communicate to produce an artefact, because different groups may choose to prioritise aspects of a process that they view as within their particular domain of expertise. However, several groups with different tools, conceptual terms, approaches and interests must sometimes work together to achieve shared goals. For example, Galison (1999) describes war-time efforts in the 1940s to design and build functioning radar equipment. Physicists and engineers that had previously worked entirely separately now had to share a space and work together to transform theories about radar capability into devices capable of radar detection. Although these physicists and engineers did not share common vocabularies and techniques, they were able to create a sufficiently intelligible common language to share ideas and practices. Galison names these physical and intellectual spaces 'trading zones,' which is a concept he and others have applied to explain 'the inevitably incomplete, but essential coordination between different subcultures [in science]' (Galison 1997, xxi).

One of the key points Galison makes, and of particular interest when thinking about methodological choices and identity, is that his radar detection collaborators retained discrete forms of group belonging based on their practical and epistemic commitments; even as those discreet identities evolved and changed in response to the experiences of

collaborating with members of other groups. He differentiates between surface level 'pidgin' vocabularies that allow members of groups with different epistemic and practical commitments to communicate with each other, and forms of more sophisticated 'creole' languages that develop and sustain as actors make particular trading zones their preferred 'home'. One of the questions I take forward in this thesis is whether or not amphibious researchers are in fact carving out new forms of identity linked to the artefacts they are creating, or if the development of their capacities across the wet and the dry are intended as capital investments in an imagined future trading zone of which they feel a part.

In terms of researchers working to build their own skill-sets and capacities in line with the development of new artefacts Joan Fujimura argues that researchers mobilise sets of theories and methods to further their particular interests. Fujimura (1988) calls these theory-method combinations 'standardized packages' and argues that certain cancer researchers in the 1970s-80s linked a particular theory about tumour growth (oncogene theory) with a particular technique for testing that theory (recombinant DNA technologies). In doing so, Fujimura argues these researchers developed a set of conventions that helped formalise a line of research, molecular biology, as a dominant form of problem solving apparatus for cancer research. At the same time, this formalisation of the most effective way to understand tumour growth and test oncogene theories also helped those same researchers to build enduring careers and reputations. Fujimura is clear that choosing to use a certain tool in scientific work is not a banal decision. On the contrary, combining tools and theories can be a formidable way to generate interest in lines of research that further career ambitions for the researchers involved.

These insights help to demonstrate that relationships between novices and experts do not simply equate to the transfer of skills from one to the other, and choosing a particular tool for a task has implications for career development. Learning to be skilful forms part of an individual's identity and belonging as part of a group. Furthermore, learning to be skilful across different groups involves creating shared resources and vocabularies and these experiences may go on to shape career ambitions, group

identity and methodological choices. These ideas help us understand automation and molecular biology, particularly ideas around automation and tacit knowledge.

2.6 Tacit knowledge and the social shaping of automation

> ‘Molecular biology techniques are very green-fingered and slow, involving a lot of "the expert's" time. Often, the only way to learn a technique is to go to someone's lab and learn it - it's often even difficult to get it from a [published] protocol. The idea [of automation] is to take the mystique out.’ (Hodgson 1990: 190)

For Hodgson (1990), quoted above, automation offered significant promise for molecular biology and his article sits in a tradition of promissory accounts of the benefits that automation will bring for science, technology, and medicine. Hodgson’s article, titled ‘Molecular biology in 2001’ is a speculative account, and I am interested in the ways in which such speculations put forward in 1990 are similar to ambitions for more recent laboratory automation. For example, Hodgson’s particular phrasing – techniques as ‘green-fingered’ and automation as a decoding of ‘mystique’ – remain in promises for laboratory automation today, albeit with different vendors offering several solutions to tackle these perceived issues. Keating, Limoges and Cambrosio (1999) posit that a central ambition for automation is to ‘flush out tacit knowledge’ from the laboratory and this stood in contrast to my experiences during my empirical work and gave rise to my central research question in Chapter 1 above. An understanding of what tacit knowledge is, and what it is not, was therefore a good starting point for explaining the desirability of automation in the biosciences.

2.6.1 Tacit and explicit knowledge (Collins)

The most prolific published writer on tacit knowledge in STS is Harry Collins. He published *Tacit and Explicit Knowledge* in 2010 and this book appears as the culmination of his work in this area. This work began with *Artificial Experts* (1990), through *The Shape of Actions* with Martin Kusch (1999), and *Rethinking Expertise* with Robert Evans (2008). This latest effort (Collins 2010) adds extra analytical categories to his earlier work. One of those categories, somatic tacit knowledge, is important to my analysis because it is with this categorisation that Collins deals with embodied knowledge. As indicated above, my interests in identity and future-expectations have clear links with embodied knowledge.

Before explaining my interest in somatic tacit knowledge, I want to begin by describing Collins' analytical framework for tacit knowledge, and the reasons he gives for introducing new categories as his thinking has developed over time.

2.6.1.1 Relational, somatic, and collective tacit knowledge

In his later work, Collins seeks to separate different forms of tacit knowledge. To recap from the previous chapter, no single definition exists for tacit knowledge. However, one simple definition would be that tacit knowledge is that part of a particular understanding that is difficult to communicate to others just by writing it down. Collins divides tacit knowledge into what he calls weak, medium, and strong tacit knowledge. Weak or 'relational' tacit knowledge is knowledge that is either tacit or explicit when social arrangements change. That is, relational tacit knowledge for Collins is the kind of knowledge that can be tacit among a group of similarly socialised and socialising humans, a form of unspoken understanding about how to and why to perform actions in a certain way. This same knowledge is relational if, when the social arrangements change, and an unfamiliar member enters the group, the how and why of the actions being performed can be made in to explicit instructions for the new community member. For Collins, knowledge about the nature of human society, 'collective tacit knowledge' is strong because groups make it durable by sharing it over time and space.

The medium category, 'somatic tacit knowledge' is a concept that Collins says most researchers have focused on, to the detriment of the understanding of the nature of knowledge. This is because somatic tacit knowledge as Collins describes it is incorporated or embodied knowledge that has to do with the nature of the human body and mind:

> It remains true that for most individuals, if not all, that the body is central to the acquisition of knowledge. This, however, says less about the nature of knowledge than has been assumed; what it does indicate is something about the nature of human beings and how they acquire knowledge. More profoundly, it also remains true that the nature of the body does, to a good extent, provide the conceptual structure of our lives, but that conceptual structure is located at the collective level, not the individual. One of the main

> projects of this book is to demote the body and promote society in the understanding of the nature of knowledge (Collins 2010: 8).

2.6.1.2 Polymorphic and mimeomorphic actions

One of Collins' aims is to demote the body in understanding how people understand their lived experiences. His work with Martin Kusch on action morphicity helps to illuminate differences between what humans and machines can do. Action morphicity is the theory that the actions humans take have a certain shape. They can be mimeomorphic, which means that the action is similar enough and consistent enough that one can copy the physicality of it without comprehending what it means (Collins and Kusch 1999). Alternatively, actions can change shape depending on the social arrangements of the individuals performing the action: 'Actions where the associated behaviours are responsive to context and meaning are called polymorphic actions.' (Collins 2010: 55).

To illustrate this point Collins proposes that the salute is a good example of a mimeomorphic action because, if done effectively, humans can repeat the actions that make up the salute similarly many times. For Collins, a greeting is a good example of a polymorphic action because the actions of appropriately greeting someone can depend on the social relationships of the people involved, and the expectations that different cultural groups have for the social norms of greeting one another. A person performing a correct salute is behaving in a machine-like way. Researchers could not program a machine to greet a human in the *correct way under all circumstances* because those circumstances depend upon an unknown and evolving set of social conditions. These conditions will change according to the situation, people involved, cultural expectations, and even time of day or year, weather conditions, and the perceived emotional state of the givers and receivers of the greeting.

> We need to understand social life to know to what extent actors are committed to carrying out an action in one way rather than another, and thus to know what might be changed in order that automation becomes a possibility. To this extent, understanding the potential for automation means, among other things, understanding the extent to which people are ready to

> begin to execute their actions mimeomorphically; this is a matter of sociology and social history. (Collins and Kusch 1999: 198)

The theory of polymorphic and mimeomorphic actions is useful for my cases as a heuristic. That is, when observing many of the actions by informants at the two case study sites (Chapters 6 and 7), I found it useful to think about how the actions they took had a certain shape. Understanding actions as being of a particular shape helps to demonstrate that robots can mimic an action otherwise performed by a human operator, but only in a very limited way. Operators make the result of the robot action meaningful, through their polymorphic actions, as they spend time agreeing upon the correctness of the results, and the necessary adjustments in the experimental conditions. Crucially, as the following chapters demonstrate, researchers in my study needed to make adjustments and to mobilise judgements of correctness across multiple knowledge communities, and over long periods. In this way, researchers carry with them a set of skills and competencies about how to work with specific systems to keep them functioning.

2.7 Embodied knowledge and 'Fingertip-feeling'

Competent researchers develop and maintain skills and must retain knowledge about how their systems work. For my purposes, studies on knowledge durability, and the relationships between sustaining knowledge and sustaining technology, particularly Donald MacKenzie's work on nuclear weapons, have been especially fruitful. Both this research (MacKenzie 1999) and collaborative work with Graham Spinardi (MacKenzie and Spinardi 1995) looks at the role of tacit knowledge in the design and testing of nuclear weapons systems. A salient point by MacKenzie and Spinardi for my purposes is that, when considering the durability of nuclear weapons, there are skills incorporated in human beings that are essential to the continuation of nuclear weapons. That is:

> Theoretical statements and instruments are portable and (within limits as regards the latter) immortal. Skill incorporated in human beings – and tacit knowledge is, quite literally, incorporated, embodied knowledge, as the German expression Fingerspitzengeful ('fingertip feeling'; intuition) reminds

> us – is portable only along with its human possessors, and shares their mortality (MacKenzie 1999: 426).

Thinking about the mortality of the skills of system builders in the biosciences, one of the potential advantages of automation is that once users program their robots, these skills are no longer mortal; they are incorporated in the instruments and, to a certain degree immortal. However, as the preceding sections have argued, this is not so straightforward. Like MacKenzie, I see the incorporated bodily knowledge of researchers in the biosciences as a form of 'fingertip-feeling'. These system builders develop an embodied expertise that is not easily mimicked by their robot platforms. As Forsythe describes above, knowledge acquisition into a computerised system always remains partial. Even when computer programmers can codify types of knowledge, programmers sustain and share the meaning of those abstract ideas through their interactions with each other. Therefore, knowledge acquisition is also socialisation. Put another way, knowledge acquisition is about learning how to be in the world of people and things, and this learning how to be comes from an attentive engagement with and through collections of people and things.

2.7.1 Life science as a full bodied practice

The ideas above are further expanded in Natasha Myers' (2015) work on learning to be a successful modeller in protein crystallography. Myers has developed a strong case for the role of biologists' bodies in generating knowledge about protein structures. For Myers, novice crystallographers are trained in how to model the shapes and functions of their proteins by developing both a feeling for the organism and a feeling for the machine (Myers 2014).

This analysis builds on earlier work by Evelyn Fox Keller (Keller 1983) that focused on Barbara McClintoch's biography as a pioneer in work on the genetic organisation of corn. Keller makes an important point that early proponents of genetics working on drosophila fruit flies did not recognise the value of McClintoch's theories on transposition. One of the reasons McClintoch's work remained outside of the mainstream theories in genetics research for several decades is that her work could not be easily assimilated in to the mechanistic theories of genetic organisation. These

mainstream theories held that genes were simple units ‘laid out in a fixed linear sequence’ (Keller 1983: x). However, McClintoch’s research programme at Cornell University focused on maize plants, not fruit flies, and as a result, maize researchers spent far longer periods observing each generation of plant specimen than did the fruit fly researchers studying genetic mutations in drosophila. McClintoch and her Cornell colleagues compared visual observations of corn kernel patterns and then conducted microscopic observations of the chromosomes to track mutations across generations. In Keller’s account of McClintoch’s research, it was this longer period of observing that allowed the Cornell researchers to develop an intuitive ‘feeling for’ their organisms, and it was this feeling for that enabled McClintoch to formulate her ideas about the effect of random ‘jumping’ of genetic organisation within her corn samples. Genetic researchers in the 1970s later revisited this theory of genetic ‘jumping,’ or transposition and recognised McClintoch’s contribution to the understanding of genetic organisation.

For Myers, building on Keller’s notion of a feeling for the organism, this ‘feeling for’ in the modelling of protein structures involves understanding proteins and functioning in a mechanistic way. However, Myers points out that this learned expertise in understanding living proteins as machine-like (developing a ‘feeling for the machine’) is only part of the story for learning how to be a successful modeller in protein crystallography. Importantly, through detailed and long-term observations of how protein crystallographers use their bodies to effectively communicate the shape and functions of proteins with one another, Myers demonstrates that ‘life science is a full bodied practice’ (Myers 2015).

Protein crystallographers develop this full-bodied practice through learning how to ‘fee[l] the spatiality and movements of the molecule by virtue of the spatiality and movements of …their own bod[ies].’ (Myers 2015: 111). Myers presents observations from her time in a laboratory with Diane, a laboratory leader and highly experienced protein crystallographer. Diane taught other laboratory members how to recognise good models from bad by using her body to twist and contort in to the shape of the molecule on the screen. Diane used her body to ‘feel the pain’ of the molecule and to know if the proposed model would be ‘comfortable’. Importantly, novice student

crystallographers did not know how to develop this feeling for their molecule at first. Diane acted as ‘an exemplar and a guide’ (Myers 2015: 103) and helped less experienced researchers to develop a sense of intuition for well folded models, and to use their bodies to think through and communicate that folding. In this way Diane also acted as an exemplar for Myers and helped her to ‘pose a new set of questions about the role of researchers’ bodies in scientific practice’ (Myers 2015: 103). As the following chapters show, I take these questions forward into my own empirical work.

2.8 Conclusion

The literature I have examined in this chapter help to show that promises about the future require further analysis, especially promissory narratives that rely on the future value of technologies. This is particularly evident when those technological promises involve the use of machines to complete tasks previously completed by human operators. Importantly, I have shown that skills are related to a person’s skilfulness as part of a group and contribute to their sense of identity and belonging in those groups; codification of skills is clearly no simple process. Furthermore, for groups to sustain knowledge and understanding over time, researchers must recognise the embodied character of knowledge, and the importance of the novice/expert relationship. To emphasise these insights, I have introduced four areas of literature.

Firstly, I presented theories about the future value of technologies. I have shown that expectations about technologies and the way vendors presented them legitimates how groups take action in the present. I drew on past research looking at automation in manufacturing and in the military in the United States to show how expectations for technologies can have unpredictable effects. Secondly, I presented arguments that link methods and tools with questions of identity. I discussed the process of identification, and how scholars link ideas about the self to constructions of professional identity. I have shown that forms of boundary-work are usefully applied to differences between professional groups in my cases, in a similar way to the boundary-work that divides science from non-science.

I have further linked Butler's passionate attachments with Ingold's attentive engagement to show that the way people conceive of themselves is through the relations they have with other people, often other people who occupy positions of control and dominance. Furthermore, I have argued that conceptions of self and relations to others are also part of the engagement between people and things; using tools and learning how to use tools forms part of those relations. These arguments help to underline the continued relevance of the social shaping of technology approach, especially the observation that the society-technology relationship is mutually shaping.

In the final sections of the chapter, I presented Collins' argument about somatic and collective tacit knowledge. Collins wants to demote the importance of the embodied character of somatic tacit knowledge, which he argues that writers overemphasise in existing literature. More than this, he says that understanding tacit knowledge as being primarily embodied in the individual is to miss the point that only through understanding how knowledge is 'embodied' in society (Collins 2010: 2), that is, understanding collective tacit knowledge, can we recognise 'strong' tacit knowledge. I argue that individuals need embodied knowledge to learn how to feel part of groups. However, perhaps this is Collins' point: for tacit knowledge to be 'stronger' (e.g. more durable) users need to embody understanding within a collective. As I argue in this thesis, I see the durability of systems and the knowledge needed to make them function as being part of an individual's 'fingertip feeling.' However, this intuition and 'feeling for' is a socialisation process that ensues from an attentive engagement between people and the care and nurture they have for the artefacts they build and with which they work. This attentive engagement is also required to make these systems work with the biological materials they need to keep alive for successful functioning of the system.

In the next chapter, I outline the methods I employed to generate the argument above and specifically highlight my interest in methods that illuminate the lived experiences of automation-driven synthetic biology.

CHAPTER 3:

Research design and methodology

3.1 Introduction

I completed the empirical parts of this study between January 2015 and April 2017. In January 2015, I received ethical approval from my university to begin the study. I spent ten weeks between January and March 2015 making regular visits to a bioengineering laboratory at my university. My reflections from this period provided a grounding in challenges faced by current laboratory users. I built on this understanding by attending practitioner events: an EU-US workshop and an industry-academia workshop during which I observed prominent speakers and analysed the debates researchers were having about the future of their fields. I conducted the main empirical work on which the thesis is based between October 2015 and April 2017 at two different case study sites in the UK. The methods I employed here included document analysis, semi-structured interviews and ethnographic fieldwork. The case studies involved spending extended periods observing practitioners at two university academic laboratories. I compared those observations of practice with policy and vendor narratives I found in policy documents about laboratory automation and the biosciences, particularly synthetic biology.

3.1.1 Facet methodology

A notable aspect of the study was my commitment to openness in terms of the possible resources for understanding my object of study: namely, automation for the biosciences. These resources included the potential places to look for objects of interest and the potential tools available to understand those objects. I chose participants for the study by attending events and observing researchers' talk and practices. I chose my methods based on the recognition that an analysis of lived experiences would best illuminate the way current researchers experienced policy promises about automation. I was influenced by my own participants' occasional playfulness in their approach to their work and the way that seemingly counterintuitive

and contingent aspects of their daily lives were missing from most published accounts of automation and the biosciences.

One approach that suited this experience was facet methodology. Using the metaphor of facets in a gem stone, Mason (2011) describes how the object of interest in the social sciences can be approached from multiple perspectives and indeed must be approached this way for appropriate understanding. Different planes and facets can cast varying levels of colour and light depending on the angle (approach) and the size and shape of the facet. Importantly, she observes that '… sometimes it is the smallest facets that create particularly intense or brilliant shafts of light and colour'. (Mason 2011: 77)

I found that by focusing on particularly salient 'flashes of insight' (Mason 2011: 80) and using those insights to shape the direction of the research, I could remain sensitive to the contingent nature of my research object. During the initial planning and pilot stages of the project, I was keen to be guided, in part, by the practices of current researchers working with automation in the biosciences. I found that ethnographic methods allowed the greatest freedom for openness in terms of lines of enquiry. What I later understood to be important and salient observations fundamentally shaped my areas of interest, as I embarked on writing up fieldwork notes from my pilot work. I see a complementarity between Mason's 'flashes of insight' and what Marilyn Strathern calls 'ethnographic moments' (Strathern 1999). An ethnographic moment is an experience of observing a particular act that, through the process of writing it down, reveals itself to be full of relevant details that require further reflection. An ethnographic moment is also anticipatory and the act of pausing to reflect on seemingly salient observations 'becomes a harbinger of new understanding' (Morita 2017: 240). I present my own ethnographic moments using vignettes and episodes throughout this thesis.

The facet methodology also helped with my own recognition that my research was not attempting a total evaluation of a subject, nor analysing a representative sample of automation in the biosciences. Rather, I aimed to combine differing saliencies and insights in interesting and perhaps playful ways, following facet methodology's concerns: '… to *create a strategically illuminating set of facets in relation to specific*

research concerns and questions: not a random set, or an eclectic set, or a representative set, or a total set.' (Mason 2011: 77).

3.2 Aims of the chapter

My aim in this study was to produce a strategically illuminating analysis of automation for the biosciences. I aimed to provide an analysis that posed a rethinking of this area and avoided the implicitly technological determinist framings found in many of the published accounts of automation and biosciences research. To achieve these aims I prioritised understanding of lived experiences through observation, and followed this up with in-depth interviews. More than this, I pursued training opportunities with my informants and learned how to use some of their equipment. At specific moments, I stood in for some of my informants and acted as their representative for external visitors. In this way, I role-played what it was like to show-off an automated system to interested science journalists and in doing so felt the same pressures, anxieties and pleasures my informants felt when they were asked to speak publicly about their systems. This methodology chapter sets out to describe how the process of designing my research methods developed during the course of the research, and how these methods led to particular moments and insights that fundamentally shaped the direction of the research as it unfolded.

3.3 Structure of the chapter

I have organised the chapter into four main sections. The first outlines the research design that I employed for the study. As I go on to describe, the design of the research was not intended to be sequential. Each of the episodes and activities I engaged in helped to shape my thinking throughout the research. I used different methods at different times according to the specifics of each episode, case study, and site-access levels. In writing up my reflections, I did not prioritise the order of the material based on when I made an observation: instead, the writing up process allowed me to see connections between different episodes and stages of the project. My choice to undertake document analysis of policy literature and pilot work in parallel originated from my commitment to understand talk and practices in tandem. In the second part of the chapter, I describe how I decided on the appropriate methods for the study, and how I relied heavily on ethnographies and interviews to understand the lived

experiences of laboratory automation and synthetic biology. The third and fourth parts of the chapter detail the way I organised my research activities and my approaches to data analysis. I end the chapter with reflections on some limitations of my study and my approach to following appropriate ethical approval processes.

3.4 Research design

I divided the research into three sets of activities. My first task was to conduct pilot work, which involved ethnographic observation, documentary analysis, and exploratory semi-structured interviews. For the second part of the research design, I conducted two case studies and these involved ethnographic observation, documentary analysis, and focused semi-structured interviews. In the third part of the study, I undertook data analysis and evidence synthesis and this involved fieldwork notes and transcript analysis and follow-up semi-structured interviews. I did not intend to implement the three parts of the research entirely sequentially because, as described previously, the research orientation remained responsive to particular insights from my research sites. I undertook continual analysis during each part of the research and modified my approach as I identified salient topics. I utilised a number of these topics when planning ongoing ethnography and interview strategies, including practitioner debates concerning problems and solutions for experimental work in the biosciences (see Chapters 4 and 5 below). However, I also understood that my research objects were inherently complex and tried to retain an openness in the overall research design. In this way, my approach aimed to emulate the 'strategic illumination' of facet methodology by not closing off lines of enquiry with fixed and predetermined hypotheses.

My focus on the 'lived experiences' of users of automation technologies in the biosciences necessarily meant that more than one case study site would offer the best chance of capturing varieties of those lived experiences. Therefore, during the pilot work I identified two UK laboratories with specific interests in using automation technologies. I chose these two sites based on a number of factors. For example, each site offered contact with researchers who had published on the topic of automation in the biosciences. Additionally, both sites carried out work with liquid-handling robotics for the biosciences. I was interested in liquid-handling robots because during the pilot

work I had experienced how challenging it was to learn how to handle liquids to complete a process.[3] I selected the two case study sites because of their apparent similarity in wanting to use liquid-handling robots to complete experimental work previously undertaken manually by individual researchers at a laboratory bench.

In addition to the apparent similarities between the two case study sites, I also recognised differences. For example, one of the case study sites had approximately ten years' experience with research projects using liquid handling robotics for the biosciences. This case study site, the Rhodes Lab (RL) had a number of active research projects and the laboratory PI, Kieran, had published extensively in the area of laboratory automation and biological experimentation. The second case study site, the Assemblers Lab, was a newly established centre aiming to develop systems and services for liquid-handling in the biosciences. Both case study sites were part of the UK academic biosciences community but each site identified differently with various groups within that community. These similarities and differences were important for my research topic because of the range of lived experiences I could observe, and speak about with my informants. Moreover, having both an established laboratory and a newly created laboratory as case study sites allowed me to compare how different groups of researchers managed their tools, particularly when system designers and system users changed over time.

I made a conscious research design choice to select both an established and a newly formed research group, each attempting to use very similar types of equipment. I needed to unpack how the established group (the Rhodes Lab) had evolved their use of tools over time, and what might be gleaned from this to help illuminate the practices of the newly formed group (the Assemblers Lab). A key driver for the design choice was a recognition that my time and resources were limited. I was keen to understand more than the local specifics of one group of actors and to compare different users' lived experiences of developing and using the same tools across multiple groups. In doing so I aimed to mitigate the potential for my study to miss broader trends in the adoption of automation systems in the biosciences by focusing too narrowly on one

[3] During the pilot, a postdoctoral researcher provided me with training to complete DNA fragment analysis using the process of 'gel electrophoresis.'

set of particular users. By choosing to observe and interview multiple sets of users, and to re-visit case study sites for follow-up work over 18-months, my goal was to understand why at this particular moment in the history of the development of automation for the biosciences separate groups of researchers were choosing to develop skills using specific tools, even as laboratory automation vendors had marketed those same tools for a number of years.

My pilot work and observations prior to the two main case studies allowed these design choices to be strategic, and to be informed by provisional background information without prejudging the outcomes of my research (Pollock and Williams 2009, Pollock and Williams 2010). For example, I combined a 10-week pilot ethnography in a bioengineering laboratory, using liquid-handling robots, with strategic observations at workshops, conferences, and project meetings to understand what some of the challenges might be for integrating liquid-handling robotics in to current laboratory practices in the biosciences. During this pilot work I learned that a significant number of existing liquid-handling platforms remained under-utilised across multiple organisational contexts, with different types of experimental tasks deemed more or less appropriate for adaptation for various automation platforms.

In the chapters that follow I present my findings and offer arguments to explain why certain automation tools were judged to be good or bad for different purposes in the biosciences. Follow up research might build on these and focus on the long-term, ongoing, operational challenges of using automation platforms in the biosciences. For example, restrictions in available funding and the time constraints of a PhD programme meant that the knowledge I produced was based on several episodes of activity limited to a two-year research window. Future research could re-connect with the Assemblers Lab group after their initial funding cycle is competed to ascertain how far their project to ‘automate everything’ (see Chapter 7) has come to fruition. This is an area of research that could be pursued as a follow-on study, and was beyond the scope of this current project.

3.5 Research methods

As I have already indicated, I chose my research methods based on my interests in the lived experiences of laboratory users. My choice to conduct ethnographic observations stemmed from my desire to compare the policy promises about laboratory automation and synthetic biology with the laboratory-based practices of current researchers. I completed analysis of policy documents to understand how vendors and policymakers presented laboratory automation and synthetic biology. Finally, I utilised semi-structured interviewing with key informants from my ethnographic fieldwork to pursue several lines of enquiry identified in my early observations. The open design of semi-structured interviews is contrasted with the use of a standardised questionnaire because an open approach to interview questions is less likely to constrain the variety of possible responses (Flick 2009). However, as indicated, I had identified possible themes and questions during pilot work and observations, and these insights provided some structure to my interviews and formed the basis of my interview guide (see Appendix 1).

I wished to link the data from ethnographic observations and individual interviews with the emergent automation strategies in two areas: firstly, at national level through policy initiatives around automation for the biosciences and secondly, at the organisational level through internal records of system development. To accomplish this I triangulated the ethnographic and interview data with document analyses of a range of policy documents (see Figure 1 below). These documents included strategic policy documents published by Research Councils UK (RCUK) and the UK government; conference and workshop submissions concerning automation and synthetic biology; successful and unsuccessful funding proposals with automation for the biosciences as the focus; and technology vendor material relating to the installation, operation and maintenance of current automation systems in biosciences laboratories.

Figure 1: Document sources

Title	Body	Date	Content
A Roadmap for High Throughput Technologies (InsightFaraday 2004)	InsightFaraday Partnerships	2004	A technology roadmap for High Throughput Technologies (HTT) commissioned by the Department for Trade and Industry (DTI). 48 pages.
Investing for growth: Capital infrastructure for the 21st Century (RCUK 2012)	Research Councils UK	Feb 2012	Strategic framework for investing in national capital research infrastructure. 40 pages.
A Synthetic Biology Roadmap for the UK (TSB 2012)	Technology Strategy Board	July 2012	Roadmap for UK synthetic biology, including 5 recommendations covering: investment and training needs; commercialisation; and establishing bodies and committees for synthetic biology in the UK. 36 pages.
Eight Great Technologies (Willets 2013)	The Policy Exchange	Jan 2013	Government policy account of £600 million investment in science and technology between 2012 and 2015. Synthesis of earlier reports (including those listed above) naming specific

			application areas targeted (including RAS and synthetic biology). 59 pages.
RAS 2020: Robotics and Autonomous Systems (KTN 2014)	Knowledge Transfer Network	July 2014	National strategy for investment in Robotics and Autonomous Systems (RAS) 23 pages.
Biodesign for the bioeconomy: UK Synthetic Biology Strategic Plan 2016 (SBLC 2016)	Synthetic Biology Leadership Council	Mar 2016	'Refresh' of the 2012 UK Synthetic Biology Roadmap, now termed a strategic plan. Further 5 recommendations: Accelerate commercialisation; maximise the innovation pipeline; build expert workforce; create supportive business and regulation environment; and build value through international partnerships. 36 pages.

3.5.1 Methodology and theoretical approach

In the case studies, ethnographies and semi-structured interviews I followed a 'social shaping of technology' (MacKenzie and Wajcman 1999) approach that understands technology as part of what makes society function. From the simplest of flint hand tools to complex military missile guidance systems, humans build and maintain the complex web of social relations that make up the world. Technologies are *part* of those relations. In other words, to fully understand how humans relate to one another, we

must understand technologies as culture (Wajcman 2006). When encountering the implicit technological determinism of policy and public accounts of automation for the biosciences, the social shaping and technology as culture approaches offered an established set of tools for unpacking over-simplified claims for the future of automated laboratories. For example, it is not sufficient to conclude that technologies are gendered in their design and use. Women's and men's identities, who they identify with, is shaped by the technological and scientific culture of their worlds (Wajcman 2006).

By understanding automation as one form of laboratory culture in the biosciences, I could begin to map some of the divergences between the rhetoric and practices of automation for the biosciences and think about some implications of those divergences. Working from participants' views, I paid attention to 'what works' with automation, specifically in which contexts and how the automated platforms were shaped by the lived experiences of the operators of those systems. In addition, I followed the operators and system designers to understand how their expertise and roles developed in relation to the systems with which they worked. I came to see that, to understand a system as 'working' involved more than describing the process of learning new skills for operators. Understanding how users were able to operate the automated systems involved seeing skills as technology too. That is, skills are far more than a simple means to an end; learning skills is also learning how to be in the world, and learning how to be in the world today is an engagement between people and things.

Ingold (1997) makes this point well when he describes skills as an 'attentive engagement.' Such an engagement contains important aspects of care and reciprocity that have their own intrinsic intentionality and meaning. This is an important point for automation in the biosciences because deskilling, reskilling and upskilling feature heavily in policymaker narratives about what actions they need to take to make automation successful in the biosciences (see Chapter 4). By recognising the attentiveness of the engagement between operators and automated systems I seek to draw attention to the implicit technological determinism in the '-skilling' agenda, and thereby offer a more rounded understanding of automation in the biosciences as socially shaped. Intellectually and politically, the social shaping approach is much

more satisfactory than the above form of naïve technological determinism. It is satisfactory because the social shaping approach recognises that users, policymakers, funding bodies, mass-media reports, and business and university managers and leaders all contribute to the development of technology. My overall aim in this study was to show how automation in the biosciences are socially shaped, and to highlight some of the contradictions and contingencies that may open up opportunities for critical reflection.

3.6 Organising my research activities

3.6.1 The pilot

I organised my initial pilot research activities in to three stages. First, documentary analysis of policy documents concerning Robotics and Autonomous Systems (RAS) and synthetic biology. Second, ethnographic observation at two synthetic biology practitioner events. Third, a ten week pilot ethnography in a biosciences laboratory using liquid-handling and robotics. The pilot work was part of my efforts to refine both the research focus and the research tools at my disposal. Later on, when research started at Case Study 1, I used experiences from my pilot work to explain some of the areas I was hoping to explore with the research team. From a methodological standpoint, it is interesting to reflect on how my informants interpreted the notion of a pilot. When describing my pilot work to a graduate technician in the laboratory, at first she was not sure exactly what I meant. The postdoctoral researcher (postdoc) helped by explaining that a pilot was 'like a proof of concept'. Perhaps because I did not see my research in this way, I was considering using different terminology to explain the pre-case study data collection during the writing up stages. However, on reflection I understood that the postdoc's version of 'proof' was similar to my own understanding of trust. In the same way that some synthetic biologists develop proofs of concept before attempting to scale-up to industrial production processes (see Chapter 5 below), I was using my pilot work to both guide my research design and generate trust in my subsequent research methods. My informants, peers, and supervisors all contributed to my having trust in the way I conducted the study.

3.6.1.1 Case study selection and initial analysis

In the second and third parts of the pilot phase, I attended two practitioner workshops as an ethnographic observer that I refer to below as the EU-US workshop and the industry-academia workshop. I also joined a biological engineering laboratory working with a robot platform. The first workshop I attended was influential in my decision to refocus my research proposal from standardisation in synthetic biology towards automation in the biosciences. The first workshop organisers focused the event on discussing the development of common standards, and how they could further enable systematic engineering using synthetic biology techniques. I had a formal note-taking role at the workshop and created a report describing the content of each session, including the debates during the question and answer sessions. I also made my own field notes at other times during the workshop and had ethical approvals for this (see section 3.9 below) prior to attending the workshop. A key outcome for me during the workshop was that, across a wide range of research interests, projects, aims, and affiliations represented at the event, the talk of automation as solving problems in the future was strong. I came away from the conference convinced that automation was a topic ripe for exploration using social science techniques.

The experience at the workshop and my reviews of grey literature led to a desire to spend time inside a laboratory with users of automation systems. The result was an agreement to spend around ten weeks visiting a UK-based laboratory to learn about its work. This laboratory was within the area of bioengineering and operated as part of an academic research laboratory focused on specific research projects and questions. In Chapter 5 I explain the importance of those few months for helping me to recognise the potential disparity between public declarations of the power and potential for automation in the biosciences and the lived experiences of laboratory users actually charged with setting up and maintaining functionality of these systems. For now, it suffices to explain that it was during conversations with the principal investigator (PI) at this pilot site that I first discussed the notion of a robot technician. The PI suggested I look into a laboratory at a different UK university that was attempting to use robots to be more than technicians in the laboratory. This laboratory was to become Case Study 1 in the main empirical part of my project.

I selected Case Study 2 in between completing my pilot study and beginning ethnographic fieldwork at Case Study 1. The work of Case Study 2 was familiar to me because of my affiliation with a social science research project studying synthetic biology. The PI of this research project had existing relationships with some members of the laboratory at Case Study 2, as well as ongoing research interests there. The initial plan was to mirror my research design across both Case Study 1 and Case Study 2. At Case Study 1, I had become resident within the laboratory and joined the research team in several phases, in 2-3 month blocks, with each day spent there at my own allocated desk, or observing the researchers when they went in to the laboratory rooms. I then finished my time at Case Study 1 with four semi-structured interviews with the key informants from my ethnographic work there. For a number of reasons, described briefly below, I was unable to secure the same level of access to spend extended periods doing ethnographic fieldwork at Case Study 2. Instead, I spent several short periods (2-3 days at a time) with the research team, following specific events or processes, and collected as much observational data as I could during these visits. I then conducted seven semi-structured interviews with most members of the research team, making additional visits for follow-up interviews as needed.

3.6.1.2 Risk assessment and mitigation

Having gone through a process of investigating potential research case study sites and making contact with potential informants at those sites, I remained aware that continued access to those sites for the duration of my project remained a risk. Initially, access to Case Study 1 presented as potentially precarious because I did not have existing relationships with any researchers in the institute. To address this I made several visits to the institute to discuss my project with the PI, and provided an information sheet with ethical approval status, and assurances about my intended approach, which was to have minimum impact on the daily routines of his laboratory team. In the autumn of 2015, the laboratory manager allocated me a desk in the team office at Site 1 and I began daily ethnographic observations. I followed the same approach for access to Case Study 2, where I had a small number of existing relationships through informal meetings with junior members of the research team.

The environment at Case Study 2 was markedly different from Case Study 1 and I was aware that securing access to Site 2 was far from certain. I understood this uncertainty as a potential risk to my ability to complete the research design I originally proposed. Because Case Study 2 was a newly funded centre about to embark on a large system installation, and the research team were in the middle of establishing relationships with several external partners, the laboratory manager provided access to me on a conditional basis. However, the initial meetings with the automation specialist and laboratory manager went well and I received verbal agreement to join the research team for a period to complete my ethnography. Unfortunately, due in part perhaps to the many pressures the centre were facing to complete the installation on time, I was asked to provide further clarifications on my intended approach and contribution to the centre during my time there (see Appendix 3: Access request for Case Study 2). The leadership team at Case Study 2 wanted more information about what I would contribute to their team and how I could add value, especially as I was asking their busy laboratory team to spend time talking with me.

The laboratory manager at Case Study 2 also clarified that at certain times it would be preferable that I gave the team space to complete important tasks, including during the two-week 'site-test' when the integration contractor handed over the system to the team. I joined the team at Case Study 2 on this qualified basis, and decided that I would mitigate the risk of insufficient ethnographic data collection opportunities by increasing the number of interviews at Case Study 2. Moreover, I used my interview guide (see appendix 1) to try to ask questions that would elicit reflective responses from my informants. I did not lead interviewees on the direction of the conversation and noticed specific comments in their answers that seemed to challenge or support earlier observations during the pilot work. This approach worked well and, in the event, I collected good data during initial observations and explored these more fully in the subsequent semi-structured interviews.

3.6.2 The case studies

I took the decision to impose anonymisation on all data collected, and the sites granted me access on this basis (see section 3.9). When writing-up the data collected at Case Study 1, I used a pseudonym, 'the Rhodes Lab' to refer to the laboratory team, and pseudonyms for each informant. For Case Study 2, I used the pseudonym 'the Assemblers Lab', and again used pseudonyms for each informant. As noted the ethnographies and interviews did not take place sequentially and I conducted periods of observations and individual interviews at both sites throughout the empirical stage of the project. I had completed the majority of observations at Case Study 1 by the time I secured access to Case Study 2, and the on-going analysis of that observational work shaped my approach at the second case study.

3.6.2.1 The Rhodes Lab (RL)

I selected the RL as a case study site following initial pilot work. The site is located within an institute for biotechnology. The principal investigator (PI) at the site has published on applications of computer science and robotics to biology. He is particularly interested in the potential for robotics and machine-learning to improve methods of biological experimentation. Furthermore, the PI views computer science as a necessary approach for understanding the complexity of biology. The research team is a mix of computer science programmers, postdoctoral researchers, and cell biologists. As Chapter 6 makes clear, often the key informants at the site displayed multiple competencies and understandings. The project team mainly focused on proof of concept applications that could demonstrate the potential for computer science to improve the way that researchers conducted scientific research in the biosciences.

3.6.2.2 The Assemblers Lab (AL)

I approached AL as a case study site through involvement with researchers on a European Research Council (ERC) project grant. AL is a newly established DNA synthesis centre with a remit to become a fully automated biosciences platform. The centre was part funded through Research Councils UK funding and formed part of a set of funding streams in the field of synthetic biology. The academic lead for AL was the PI for a research laboratory and AL originally operated as a separate unit within that laboratory. During the latter part of my study AL was moved out of this one

academic laboratory and a governance committee was set up to run AL, with input from academic leads and managers from other parts of the institute. The AL team included cell biologists, software programmers, automation engineers, designers, and technicians. Again, the functionality of AL often depended on interactions between multiple knowledge communities. During my time at AL, the team were undergoing the initial automation set-up phase with support from a contracted integration company; the team did not complete live jobs on the AL system during my time there.

3.6.3 Data collection

After getting agreement from the PI at each laboratory, I began data collection using ethnographic methods. These ethnographies involved the case studies assigning me a temporary desk space at each laboratory, attending monthly and weekly laboratory meetings, sharing break and meal times, and extensive shadowing of key informants at each site. A key informant was a person I identified as having direct experience with using the automation system. Following ethnographic observations, I identified a minimum of five interviewees at each site. After follow-ups and supplementary work, I conducted eleven interviews over the two case studies. Additionally, as indicated previously, I interviewed five automation specialists and policy makers, as well as conducting participant observation and informal conversations with informants at three events in the UK and Spain. I also completed fieldwork notes were during my ten week pilot ethnography in early 2015. My fieldwork notes were first handwritten and then typed up into daily reflection logs. All interviews were audio-recorded and transcribed as Microsoft Word documents using Express-Scribe software.

3.7 Data Analysis

3.7.1 Data analysis during the pilot work

The data analysis for the pilot work involved detailed review of the notes and daily reflection logs taken during the pilot ethnography and workshops described above. For the EU-US workshop, I compiled a report on each session of the workshop and used this report to identify the key themes to take forward into the case studies. During the industry-academia workshop, I met with an external relations person based at the

Case Study 2 research institute. In agreement with this contact, I wrote up my experiences of the workshop for publication on the institute's website. I used this online article and the materials gathered during the workshop, including notes and images of presentation slides, to develop themes identified during the case studies. In addition, as outlined in Chapter 5, I interviewed an automation specialist following the industry-academic workshop. The transcript from this interview was one of the three transcripts I used to help inform subsequent interview question planning (see section 3.7.2 below).

3.7.2 Data analysis during the case studies

I collated and reviewed the interview transcripts for the two case study sites to identify emerging themes. I analysed a sample of three transcripts through an initial 'hand-coding' exercise by manually organising data in to themes. Using this method, I generated a draft theme-code template. This template was an iterative document allowing me flexibility to develop the coding further as I analysed each new transcript. This approach to analysis proved useful and I proceeded to manually code all case study transcripts to complete a first pass of the interview dataset. This preparatory work on theme coding enabled me to review each of the transcripts as the case studies progressed and use initial analyses to inform subsequent data collection. Once I completed all manual coding, I imported this dataset into the qualitative data analysis software package NVivo.

My data collection at the case study sites also required extensive note taking and writing up of observations, as outlined in section 3.6 above. I found that by typing up handwritten reflections from my daily reflection logs I was already beginning to think through and analyse my data. To build on this progress with data analysis I produced three separate fieldwork reports that contained summaries of the daily reflections logs and initial thematic analyses of connections between those reflections. I presented these three fieldwork reports to my supervisors and we discussed areas to focus on in subsequent fieldwork. I imported all fieldwork notes, documents, secondary data and interview transcripts to NVivo software and I categorized according to the emerging themes at my case study sites. I used NVivo to generate codes, segment text and filter the data, and to describe, label and group together different themes. By using

qualitative software I enhanced my ability to ‘sort, sift, search and think through the identifiable patterns as well as idiosyncrasies [in my dataset]’(Lu and Shulman 2008).

3.8 Technician involvement

An initial ambition for work at both of my case study sites was to observe and interview technicians working with automated platforms. My aim was to understand how technicians worked with newly designed and implemented automation systems. I wanted to understand how these new technologies interacted with established technician roles in these labs. A major insight from the initial three month pilot work was that the concept of a ‘robot technician’ was beginning to circulate among automation specialists in the biosciences, even as I observed the apparent underuse of these robot technicians by these same specialists. I originally hoped to observe and interview technicians currently employed in academic biosciences laboratories, particularly technicians working in laboratories that had an interest in using liquid-handling robots more extensively.

Case Study 1 did employ one graduate technician to work with their systems. However, post-doctoral researchers or PhD students performed the majority of daily work on the platform at Case Study 1. Case Study 2 employed one technician, albeit by the research laboratory within which AL first launched. I observed this technician briefly and conducted a follow-up interview. The content of this interview was extremely useful for understanding how the institution had changed over the preceding 20 years, and how different laboratories and services had been organised and supported by a number of technicians. These technicians were often women, and either worked in the ‘media kitchen’ located in the basement of the institute, or had responsibility for glassware and other cleaning duties on one of the six floors of laboratories in the institute. This interview acted mainly as background to understanding the way that facilities in the institute had changed over time, and helped me to see a trend towards centralisation, and that the AL was the latest example of this trend. I see opportunities for future research in to the changing roles of technicians in academic biosciences laboratories, especially by creating a set of oral histories with different generations of technicians. This ambition was beyond the scope of the study I present here.

3.9 Research site ethical approvals

This research was categorised as requiring level 1 ethical approval by the University of Edinburgh research ethics panel (see Appendix 2). I conducted this research with professionals and the content of the research was the lived experiences of those professionals. In some instances, informants spoke of personal experiences and gave detailed biographies and career histories. Additionally, informants sometimes gave frank accounts of theirs and others' research practices, as well as providing detailed histories of their research institutes. To enable frank and open discussion I gained consent from each informant to participate in the research on an anonymous basis. I produced a consent form (Appendix 4) and information sheet (Appendix 5) for each participant detailing this intention to anonymise, as well as my intention to take notes during observations and audio record during interviews. All participants agreed to these terms and signed the consent form for my records. I gave each informant the option of receiving a copy of the signed form, and well as receiving a copy of the transcript from his or her interview.

3.10 Conclusion

In this chapter, I have outlined my research design for the study and the methods I chose to conduct the research. Through pilot work, I established that automation was a key research object for understanding the academic biosciences, and I identified a number of locations to study laboratory automation. The research design was intentionally open-ended to allow my initial insights from conducting the pilot work to be added to and enhanced through explorations at longer-term case study sites. My primary research methods were ethnographic observation, semi-structured interviewing and document analysis. I have shown in this chapter that ethnographies were essential for developing my understanding because I was interested in the lived experiences of laboratory users. Moreover, I have shown that I needed to conducted interviews to ask questions of my informants, understand diverse perspectives, and to hear different accounts of their experiences of laboratory automation. Finally, I have shown why document analysis was important for understanding how policy makers and vendors constructed particular promissory narratives about laboratory automation in the biosciences.

Ultimately, I have explained my approach as a combination of Mason's 'facet methodology' and Strathern's 'ethnographic moments.' By explaining that I used flashes of insight from particular moments in my ethnographies, I have demonstrated how I remained sensitive to the contingent nature of my research object: laboratory automation in synthetic biology. This chapter has also outlined potential limitations in my approach and suggested possible areas to focus on in future research in this area. I have remained committed throughout this thesis to the facet methodology ideals of playfulness and saliency through attention to flashes of insight. I have conducted my research design and chosen my methods to best match those ideals. In the next chapter, I review policy and vendor accounts of laboratory automation technologies. These accounts provided the background to the user experiences I analyse in Chapters 5, 6 and 7. By understanding the complexities of the promissory narratives put forward in the policy accounts in the next chapter I was better prepared for capturing particularly salient flashes of insight in subsequent ethnographic fieldwork.

CHAPTER 4:

Promissory narratives: defining problems, debating solutions

4.1 Introduction

> '…investment in automated high-throughput bioscience facilities… will radically increase the speed with which bioscience can be progressed…' (RCUK 2012: 19)

In the first half of 2015, I explored several options for conducting the empirical work for my proposed thesis. As I outlined in Chapter 1 this initial thesis topic concentrated on efforts to standardise elements of biosciences research, under the rubric of synthetic biology and its attempt to increase the importation of engineering principles and practices into biology. Although examples of literature which expressed a need for more standardisation in synthetic biology (Arkin 2008, Müller and Arndt 2012) were available, it was more difficult to find examples of standardisation in practice. My study sought, therefore, to track standardisation as policymakers and system-users brought it into being through their practices. As Chapter 5 below demonstrates, automation figured strongly in this policy and practitioner-led effort in bringing into being a more orderly and standardised bioscience practice. In Chapter 5 I review what was being *done* and by whom in relation to promissory narratives for automation in synthetic biology. In this current chapter, my focus is on what policy makers and system vendors said and wrote about automation for the biosciences.

This chapter illustrates the way in which automation-driven synthetic biology appears in some policy narratives as an area of research that is still emerging but that is both desirable and necessary for advancing the biosciences. My analysis further suggests that policy and practitioner narratives link the progression of the biosciences to the standardisation of synthetic biologists' practices in the lab. Part two of this chapter explores alternative options for the standardisation of bioscientists' practices that do not involve any significant automation in the laboratory. Once we can see that the future of the biosciences is very much open to interpretation, it becomes vitally important to understand how policy makers and system vendors add their voices to this debate. It is important to analyse policy promises, as I have stated in the previous

chapters, because by speculating about possible futures, policy makers and practitioners are legitimising actions in the present. If one particular version of the most desirable future becomes dominant, for example speculating that automation will have an ever increasing role in the laboratory, attention and resources may be drawn to those speculations and thereby influence the trajectories of development. My own research, described in detail in Chapters 6 and 7, suggests that there are complex forces that influence judgements about good tools and the right result. However, my findings also suggest that large-scale capital infrastructure in automation platforms for bioscience research were one option among many open to policymakers and funders in this area.

To understand the kinds of policymaker and vendor promises I found by reviewing the literature below, I present five areas of promissory narratives for automation in the biosciences:

- (Narrative 1) Automation will result in more **time** for researchers (because robots are more efficient and more accurate, especially for repetitive tasks).
- (Narrative 2) Automation will enable greater **experimental space** (i.e. increased parameters and the ability to tackle problems with very large numbers of variables).
- (Narrative 3) Automation will enhance the **reproducibility of experimental results** (by breaking down experiments into recordable steps and standardised protocols).
- (Narrative 4) Automation will increase **technological capacity** (making laboratories more competitive in the international funding arena).
- (Narrative 5) Automation will provide further **opportunities for commercialisation of products and services** (either directly by using automation to build DNA, or indirectly by creating research economies based on consumables and service plans).

4.2 Aims of the chapter

My aim in this chapter is to understand the policy motivations for investment in automated laboratory technologies, particularly automation for synthetic biology. Each of the documents reviewed (listed in Figure 1 in Chapter 3) engages in various ways with the need to establish an appropriately skilled workforce for contributing to a burgeoning bioeconomy, capable of using new laboratory technologies for maximum benefit. This imagined upgrading of laboratory systems also therefore implies the need to recruit and train new biosciences researchers with different kinds of technological expertise, or a process of 'upskilling' for an existing community of users. The upgrading of instruments and upskilling of researchers I argue, forms part of a set of narratives that will need sustained empirical enquiry. My further aim in this chapter is to understand the details of these promissory narratives, and to understand how current laboratory users develop their skills through an attentive engagement to their tools. Laboratory users hone this attentive engagement over time, and the training of others involves showing how to be attentive and what deserves attention.

Choosing to introduce newer machines because they are in some senses 'better' than existing tools and practices requires users to shift their attention and engage differently with their tools, and with each other. One example of this, as discussed in Chapter 6 below, is using an Agilent bioanalyser instead of gel electrophoresis to perform DNA fragment analysis. The bioanalyser requires users to pipette small quantities of samples into 12 small wells on a chip. Researchers pressurise the bioanalyser chip using air from a syringe and electrophoretically separate samples through microchannels. Researchers at Case Study 1 preferred to use the Agilent machine because they could analyse 12 samples together in under an hour. Gel electrophoresis was many times slower in comparison. However, using the Agilent machine meant that researchers needed to learn how to use chips effectively. In one case, an informant at Case Study 1 complained about a colleague because s/he had not removed their chip from the analyser the day before which meant the previous user had clogged the 12 pins and they now needed to clean them. Therefore, users' attention needed to shift from voltage requirements when using gel-based electrophoresis, and think about chip care requirements using the bioanalyser. When different users were not attentive to

this latter requirement, they became the recipients of strongly worded messages on post-it notes from their colleagues.

Thinking about the electrophoresis example above, it is often very difficult to make clear predictions about how and why one technology will be better than another for biological experimentation. The unexpectedness of the benefits and challenges of laboratory automation are often missing from policy accounts in these areas. As I demonstrate below, for example, report authors now frame automation as a key underpinning technology for biosciences research and make predictions about the benefits it will bring. To understand this phenomenon, section 4.5 of the chapter reviews Research Councils UK (RCUK 2012) investments in capital infrastructure for synthetic biology, along with subsequent roadmaps and strategic plans which cite automation as essential tools required for progressing the biosciences. The chapter then goes on to explore problems with current practice, including the reproducibility and reliability of results, before examining academic and commercial solutions put forward by businesses and policy advisors.

4.3 Structure of the chapter

I begin this chapter by reviewing policy documents, strategic plans, and roadmaps relating to robotics, automation and biosciences laboratory research in the United Kingdom (UK). The second part of the chapter analyses alternatives to using robots to standardise the biosciences and achieve science that is more efficient. I explore discussions concerning possible alternatives to laboratory automation, including using IT technologies to record, communicate and improve the practices of current laboratory users. It is evident that some of the same perceived deficiencies identified in the biosciences by automation advocates (non-standard protocols, human error, and reliability) are shared by other academic and commercial representatives elsewhere (e.g. Klavins 2015, Brown 2016). Although agreeing on the need to improve and modernise biosciences research practices, these alternative researchers, technology makers, and service providers offer a different set of solutions which do not rely upon using laboratory robots in a significant way. The chapter finishes by reflecting on the significance of differing narratives for the future of the biosciences, particularly synthetic biology. I link back to theories concerning the future value of technologies

and think about if and how policy makers are legitimising the actions of automation advocates now by raising expectations for the future value of laboratory automation solutions. As I go on to argue, some policymakers link the future of synthetic biology with the future of laboratory automation; one clear point of intersection for these policymakers is the need for standardisation.

4.4 Background to standardisation in synthetic biology

Before exploring policy and practitioner narratives, it is necessary to re-emphasise some of the specific technical issues concerning standardisation in synthetic biology. Early proponents of synthetic biology drew parallels between engineering biology and engineering in other fields. For example, Arkin (2008) proposes three areas that require standardisation for synthetic biology to realise its potential as an engineering discipline: characterisation, manufacturing, and sharing. He argues that knowing the functions of parts in any system, from designing screw threads to creating internet addresses, is essential to any engineering design process. An example from synthetic biology is the 'parts-based' approach. The aim for synthetic biologists pursuing a parts-based approach is to decompose genomes of living systems into standardised parts with predictable properties and functions (Endy 2005).

This modular vision of biological systems becomes 'an embodiment of engineering standards' (Arkin 2008: 771) through the production of datasheets which are documents that define the characteristics of a biological device according to known functions and behaviours. The challenge in producing well-characterised genetic parts is that researchers determine the range of functions and types of measurement[4] according to their goals, backgrounds and tools. These goals may not map directly between research team members or across institutions. For example, a standard datasheet that excludes the 'protein fusion' properties of a particular part may render that device invalid for a molecular biologist, especially if these biological properties have functional consequences for their work. The different epistemic commitments of the writers of a datasheet, who often have computer science and software engineering

[4] For a detailed review of how a metrological concept, such as length, is only 'made-to-mean' through the operations in which it is determined see Schyfter (2015).

backgrounds, may not allow for the diversity of purposes to which more biologically inclined researchers might want to apply these datasheets (Frow 2013).

One distinctive feature of synthetic biology is the way that communities of practitioners have been involved in manufacturing standard parts libraries, through the International Genetically Engineered Machine (iGEM) competition. The organisers of this annual series invite entries from teams of undergraduate students to compete for prizes. A range of researchers associated with the field of synthetic biology form judging panels and rank teams against a range of criteria, including the quality of team contributions to, and uses of genetic parts in a library of standard 'parts,' known as the BioBricks library (Smolke 2009). The iGEM event also attracts international commercial interest and both organisers and entrants can receive significant private sponsorship. iGEM judges award teams' gold, silver, and bronze prizes for taking a standard set of biological parts from a central repository before the summer and working to design novel devices and applications to present at a final in the autumn. Interestingly, teams cannot achieve top gold prizes unless they contribute new parts to the repository according to the standard format. The competition rules are refined each year to reflect changes in value systems, including, for example, whether quality of characterisation should replace quantity of parts when awarding team medals (Frow and Calvert 2013a).

Social scientific empirical work has demonstrated that iGEM teams often struggle with the existing 'standardised' functionality of parts during laboratory work, which redirects their energy to refining existing parts and away from contributing new ones. This messy and unpredictable work is often then represented as a coherent narrative using engineering terminology in subsequent competition finals' presentations (Frow and Calvert 2013a). The idiosyncrasy of each team's manufacturing process may therefore be lost as they make an effort to present their work as successful engineering to a wider audience. Here we can see that interest in efforts to characterise, manufacture and share a set of standardised genetic parts has involved users adapting standardised designs and approaches in order for those designs to meet their specific needs. Understanding the effort required to make even the same part work *in the correct way*, for a *specific set of users* is therefore essential to an adequate

understanding of when standardisation works. As my empirical data to follow further demonstrates, the same applies to an adequate understanding of automation in the biosciences. I now explore how policymakers have presented automation as a way to cut out idiosyncrasies in synthetic biologists' practices, particularly the view that automation will increase standardisation and promote reproducibility of experiments.

4.5 Part One: Policy narratives for investing in automation for bioscience laboratories

Synthetic biology, along with robots and autonomous systems, were two of the 'Eight Great Technologies' put forward by David Willets (Willets 2013) and publicly adopted by the then Chancellor of the Exchequer George Osborne (Osborne 2012). The Willets report was the distillation of several reports published between 2010 and 2012, including RCUK (2012) above, and it committed the government to £600 million of capital funding in research infrastructure until 2015 (House-of-Lords 2013). The full list of eight technologies is big data; space; robotics and autonomous systems; synthetic biology; regenerative medicine; agri-science campuses; advanced materials; and energy. The inclusion of robotics and automation as important platform technologies *within* synthetic biology is less well publicly documented in policy accounts, which is one of the motivating factors for the current chapter.

There are multiple examples of economic and capacity-building arguments for investing in Robotics and Autonomous Systems (RAS) in UK policy narratives (e.g. Patchett 2014, Howard 2015, InnovateUK 2015). UK Research Councils, policy advisors and government departments (such as the Department for Trade and Industry) cite sources from the US-, Japan- and UK-based industry and academia for inspiration and guidance on how best to capitalise on RAS in the UK (InsightFaraday 2004, EPSRC 2017). An emerging strategic vision for UK RAS published in 2014 separates automation and control systems from 'fully autonomous systems' and their potential benefits. For example, all eleven of the featured application examples described in the 2020 national strategy on RAS have significant elements of programmed software. As with the autonomous car example in Chapter 1, however, the autonomy of a self-driving car is for the most part a combination of sensors and automated software

programmes that carmakers including Google use to replace actions previously taken by human operators.

I compare 'fully autonomous' RAS to narratives surrounding laboratory automation and find that machine-learning and automation (e.g. laboratory robots) appear together in narratives of High Throughput Technologies (HTT) but that so-called 'non-sophisticated automation' is the primary target at present in synthetic biology (SBLC 2016: 15). Presented in this way, the SBLC report – *A Synthetic Biology Roadmap for the UK*, published in 2012 – endorses a view that the biosciences need to get on with the relatively simple tasks of non-sophisticated automation (e.g. pipetting liquids) and that moving liquids from one place to another involves only simple decision-making which robots can easily take on. The ambition then is for RAS strategies to go 'beyond automation' (KTN 2014: 4) and begin to use machine-learning for revolutionising and progressing the biosciences. Subsequent chapters of this thesis help to demonstrate the limitations of these ambitions, and show that practitioners in the biosciences are unlikely to go beyond automation in the near future. Those chapters show that it is a thoroughly 'attentive engagement' (Ingold 1997) with, and understanding of, their tools which helps practitioners to have confidence in their experimental results. However, for policy writers new RAS technologies will have significant impacts on many fields, including the biosciences.

Since 2013 there have been several exercises and documents published examining the potential impact of RAS technologies (e.g. Manyika et al. 2013, ScienceWise 2013). For example, in 2014 the Technology Strategy Board (now Innovate UK) published the Robotics and Autonomous Systems Special Interest Group (RAS SIG) 2020 National Strategy. This document envisions RAS technologies as drivers of significant economic and societal benefit with the potential to transform the way that goods are produced and services delivered (KTN 2014). Furthermore, there are narratives emerging within academia which imagine robots as key technologies for improving scientific understanding and increasing productivity in the coming years (Yang and McNutt 2016). In these policy documents, the UK is presented as a potential world-leader in developing RAS technologies across various industries. The report authors argue that the country will derive economic benefit from the

improvements in precision, control, speed, efficiency and safety that these technologies offer. Policy narratives of RAS focus on the capacity building properties of these technologies for raising wealth and production rates as well as overcoming our human limitations (KTN 2014).

This focus on the income and productivity gains enabled by RAS have specific articulations in UK research council funder policy initiatives. For example, in 2012 the Research Councils UK published 'Investing for Growth: the RCUK Strategic Framework for Capital Investment'. The framework identifies a national need for 'underpinning infrastructure' (RCUK 2012: 9) across many UK research specialisms. The report highlights investment opportunities and challenges in a number of areas, including: food and water security; health, disease and ageing; population change; energy; manufacturing; scientific understanding; and synthetic biology. It is the last two of these investment areas that are of interest for this chapter, first because of the report's focus on laboratories as important sites for new automation tools and second because proponents of the field of synthetic biology have invested heavily in laboratory automation technologies (see section 4.5.1 below).

The *Investing for growth* report (RCUK 2012) authors recognise a requirement for researchers to have access to 'state of the art' facilities in order for national centres to maintain competitiveness in research on the international stage. This capacity building for the UK will be realised through 'exciting scientific discoveries [that are underpinned by] … developments in instrumentation technology, IT and automation…' (RCUK 2012: 16). By upgrading existing systems and investing in new ones, the *Investing for growth* report authors hope to generate a virtuous cycle of investment and return as large and mid-sized laboratories buy the latest automation tools and train a new generation of researchers to use them. As I go on to present in Chapter 7 particularly, calls for financial returns on RCUK investments do make it through to some researchers. However, in the day-to-day operations of an academic biosciences laboratory, even one system builders have designed to be fully automated, and to become a commercial profit-making service provider, income generation is not at the top of system users' priorities.

In terms of creating large-scale automation centres in the UK, policy makers tend to frame competitiveness as enabling scientific discoveries with the potential for boosting the economy. These discoveries, so policymakers claim, will help researchers create new products for new markets. Alternatively, income generation may take the form of marketing and selling instrumentation technologies to other potential users. The links being made by the report authors, between scientific discoveries, new technologies and economic growth, are not new and are sometimes labelled the 'linear model' of innovation. Briefly, the linear model of innovation postulates that '… innovation starts with basic research, is followed by applied research and development, and ends with production and diffusion.' (Godin 2006: 639). There are many examples demonstrating that this sequential view of innovation is rarely so straight forward (e.g. Kline 1985). Indeed, thinking back to Gieryn's concept of boundary work (Gieryn 1983, Gieryn 1995) the first question one asks is: how are basic and applied research demarcated, and who decides what examples count under each classification? STS work in this area demonstrates the importance of boundary definitions among different groups of scientists, and how the concept of 'basic research' has been used rhetorically and strategically among practitioners and policy makers, albeit with unpredictable effects on research practices (Calvert 2002).

Edgerton (2004) points out that the 'linear model' has become a straw man for science and technology analysts wanting to critique or support perspectives based on the inherent value of scientific discoveries and technology for economic development and he argues that such a linear model may never really have existed in the history of science. However, as I demonstrate below, policy makers do imagine a future in which academic researchers enter into research economies with technology vendors by purchasing consumables and signing up to lucrative service contracts. This is not a linear model of development as Godin defines it above, with basic research leading to applied research, leading to increased products and economic growth; rather, the assumption is that the purchase of automation tools to conduct all forms of research will create commercial partnerships that will boost jobs and income for technology vendors. This view retains a partial linearity, however, in the implicit assumptions that vendors will diffuse any increased profit to help build the wider economy. Policy

makers in the biosciences argue that, with or without increasing the rate of scientific discoveries, increased automation and laboratory IT infrastructure will help establish and maintain an economy of related companies needed to keep the technologies operational, including the suppliers of consumables (RCUK 2012: 17).

From the range of possible fields and applications likely to benefit from rapid investment in automation infrastructure (described above) the RCUK framework concludes with a review of synthetic biology. The Technology Strategy Board (TSB) published a UK Synthetic Biology Roadmap in 2012, which details a host of potential benefits they could derive from further developing the UK's presence in the field. These benefits include a strengthening of foundational and applications-based research which, it is claimed will allow the UK to make a leading international contribution to recognised global challenges (in health and the environment for example) (TSB 2012: 5). The UK roadmap identifies a number of 'essential facilities' needed to realise the field's potential including DNA synthesis centres, DNA sequencing centres, and robotics platforms (TSB 2012: 31). For policy advisors writing the *Investing for growth* report insufficient investment in robotics and automation undermines the very success of synthetic biology. The report states that the UK has a strong academic and commercial base in synthetic biology '… however there are significant gaps in the availability of and access to cutting edge infrastructure that undermines these other success factors and that in time will seriously weaken the UK's overall competitive position.' (RCUK 2012: 36).

4.5.1 Biodesign for the bioeconomy

In 2016, the Synthetic Biology Leadership Council (SBLC) published a 'refresh' of the 2012 UK Synthetic Biology Roadmap. This new strategic plan, entitled *Biodesign for the Bioeconomy* (SBLC 2016) puts forward a vision for synthetic biology as more than an exciting emerging science with multiple useful potential applications. The report authors view synthetic biology as an essential element of building a robust economic position in the UK and ongoing investment is required to grow a burgeoning 'bioeconomy'. The *Biodesign report* authors state that the new strategic plan is to be read in parallel with the 2012 roadmap but sets out specific deliverables, particularly around feeding an 'innovation pipeline' (explored further below). There are several

areas of strategic importance discussed by the *Biodesign report* authors, including acceleration of commercialisation in the field; maximising the capability of the innovation pipeline; and building an expert workforce.

The *Biodesign report* conveys a sense of urgency in translating recent advances in synthetic biology into commercial opportunities. The authors recognise that funders have invested significantly into the automation of laboratories, and seek action to maximise the return on this investment in new research infrastructure:

> Rapid progress has focused attention on the increasing importance of digital biology and laboratory automation in unleashing a new business sector of biodesign. Over £300m ($450m) of public funds have been invested in addition to substantial private investments. A focus on translation of this research base is now needed to capitalise upon the competitive technologies that are emerging. (SBLC 2016: 13)

DNA synthesis foundries funded through the Research Councils' Synthetic Biology for Growth Programme (BBSRC 2012) formed part of allocation of funds for UK-wide robotics and automation facilities. One motivation for creating DNA foundries is that DNA synthesis is viewed as a key part of the biodesign approach, advancing research from reading (sequencing) to writing (synthesising) genomes (SBLC 2016: 7). Early uses of the term 'biodesign' include the Stanford University programme in 'Biodesign', which started in 2001. The name biodesign came from students on the medical device programme at Stanford, and reflected the interdisciplinary ambitions of biomedical technology makers to engineer devices with clinical applications (Brinton et al. 2013). The term has been picked up by promissory groups in synthetic biology to mean designing with living things (Cumbers 2015).

For the *Biodesign report* authors, the ambition for automation is greater than for DNA synthesis because along with improvements in metrology and miniaturisation automation will realise a vision to move experimental sciences into an area of 'design-build-test' advanced operability (SBLC 2016: 15). The concept of design-build-test operability for synthetic biology refers to applying engineering design principles to the construction of synthetic gene networks. The ambition for using such approaches in

biology is to 'streamline the practice of biological engineering' (Agapakis 2013). The implications of this stated goal are that biodesign will take the automated tools of synthetic biology and improve the productivity of biosciences researchers in other related fields. Additionally, for the *Biodesign report* authors, advances in software development and automation tools can and should be capitalised upon by biosciences institutes to realise commercial applications and build the bioeconomy (SBLC 2016: 16).

This process of building a flourishing bioeconomy through biodesign rests upon ensuring that all stages of an 'innovation pipeline' are considered. The authors define an innovation pipeline as '… the entirety of researching, developing and testing novel processes, products or service…' (SBLC 2016: 7). The pipeline, according to the *Biodesign report* authors, will be pump-primed by ensuring that they support the relatively young field of synthetic biology to continue work on 'foundational research' by developing the requisite underpinning platform tools. Here we see the argument that alongside the use of automation in DNA synthesis and for advanced manufacturing capabilities, less-established (or 'immature'[5]) foundational research also relies upon 'the comprehensive use of automation (e.g. laboratory robots)' (SBLC 2016: 16). This is how the *Biodesign report* authors position the innovation pipeline, fed by laboratory automation, and affecting the 'entirety' of the research process.

Moreover, the *Biodesign report* authors argue that the introduction of laboratory robots and high-throughput analysis techniques, along with accurate metrology and standardisation, will facilitate increasing reproducibility in biosciences research. By linking automation, reproducibility and products together as part of an 'innovation pipeline' the *Biodesign report* authors elevate synthetic biology, and the platform tools required to practise it (e.g. laboratory robots), as an investment with multiple upsides, not least of which is the ability to solve a perceived 'reproducibility crisis' in the

[5] In policy accounts, synthetic biology is often seen as an 'emerging' discipline that is not fully developed. By creating comic books and competitions about synthetic biology early advocates also had a reputation for playfulness. I return to the theme of serious/playful in Chapter 7 below, but for now wish to highlight that policy accounts emphasise the ordering potential of automation. This idea was found again at a practitioner workshop (see Chapter 5 below) when a speaker said standards were needed to make biology in to a 'serious science.'

experimental sciences. As my empirical data shows in Chapters 5, 6, and 7, the authors have an oversimplified understanding of the orderliness that robotics can bring to the biosciences; reproducibility is about trust and confidence in the methods and the results of an experiment, and users of different automation systems bring their own approaches for garnering this trust.

A further recommendation in the *Biodesign report* is to build an expert biodesign workforce. The report authors note that synthetic biologists need expertise from different disciplines and while Doctoral Training Centres and Higher Education Institutes can promote multi-disciplinary learning, it is unrealistic to expect equally sophisticated expertise in all fields, including automation and biology:

> A successful synthetic biologist has to possess skills in one or more of maths, engineering, programming, automation, biology, biochemistry and biomedicine. Whilst it is impossible to have significant expertise in all of these disciplines, it is essential that a synthetic biologist can communicate skilfully within multidisciplinary teams. This flexibility is difficult to teach formally and is more likely to result from working and training within a multidisciplinary environment. Cultural as well as technical differences must be accommodated and assimilated. (SBLC 2016: 19)

This *Biodesign report* portrait of a successful synthetic biologist is one of flexibility and skilful communication across disciplines. Importantly, the *Biodesign report* authors recognise that being successful in this multidisciplinary space is difficult to teach formally, and scientists are likely to learn best through close proximity with other scientists. A further requirement, for the *Biodesign report* authors, is that to become a successful synthetic biologist researchers must accommodate and assimilate cultural differences among different disciplines. This cultural assimilation is a form of standardisation but applied to the scientists in this instance. As I will show in the following chapters, standardisation of the genetic structures in synthetic biology is often about fitting standards to particular needs of different groups. The report proposes that groups of researchers from different backgrounds will assimilate their practices under the auspices of being successful synthetic biologists. However, that

assumption seemed disconnected from my experience of observing successful scientists in my study. This is especially relevant because judgements of success and failure are part of the informal training detailed by the report authors.

It is not clear from the *Biodesign report* what, if anything, could be done to understand the needs of existing laboratory users in the biosciences. In action point 1.5 the authors suggest that studies could be made to find out 'whether or not' massive increases in funding are needed to profit from modern robotics. However, there are no details on how such a study might be undertaken or if and how current laboratory users would have opportunities to participate. I argue that this kind of study could be undertaken, given enough time and resources, but that the most likely outcome would be ambiguous, with some laboratories positively affected by further robotics infrastructure and others not. Another way to think about this is to examine what is meant by 'profiting from modern robotics.' (SBLC 2016: 15) The generation of income that surpasses the original investments in a platform is one way to think about profit. It is more difficult to assess the intellectual profits, or those profits the institution might make from the development of robotics and from having associations with 'leading-edge' technologies. In any case the subsequent action point, 1.6, in the *Biodesign report* offers examples of investment and loan-guarantee programmes that would be appropriate if significant further investment in laboratory automation is found to be needed (SBLC 2016).

What is clear is that the *Biodesign report* authors see a real opportunity to boost productivity in biosciences laboratories. Setting out a timescale the report authors predict that in the next three years a combination of low-cost synthetic genes and 'simple to use, cost effective, off-the-shelf laboratory automation…' (SBLC 2016: 15) will transform synthetic biology. The biggest hurdles for achieving this, however, are the lack of automated facilities, and a lack of the right skills to be able to use the systems effectively among the current workforce:

> The main barrier to uptake is reported as being changes in the approach and skillsets of researchers and easy access to robotics. Although the robotics required by synthetic biology are of modest sophistication they are currently

> poorly represented in both public and private biological facilities. (SBLC 2016: 15)

In the next section I examine how the policymaker judgements above, about a lack of sophistication in the automation of biological laboratory facilities, also extend to judgements about a so-called 'reproducibility crisis' in the field.

4.5.2 Reproducibility, reliability, and precision

Another promissory argument found in the policy literature for changing the way researchers practice experimental science is that currently too many scientists struggle to reproduce other scientists' results (e.g. Corey et al. 2014, Fishburn 2014, Baker 2016). Reproducibility of results is defined by Goodman, Fanelli and Ioannidis (2016) as the ability for one person or group to generate findings that are close enough to other published results by following the methods set out by the authors behind the experiment being repeated. The sociology of scientific knowledge (SSK) has shown that judging what counts as 'close enough' between experimental findings is a matter that requires empirical attention (Barnes, Bloor and Henry 1996). From my experiences speaking to practicing scientists, the repeatability of experiments is central to what they consider the unique potential for scientific knowledge claims. That is, these claims are not idiosyncratic musings of an individual but rather reflections of phenomena that can be verified by other scientists, and therefore have a truth-value that will be sustained over time.

SSK does not attempt to grapple with the truth-value of knowledge claims based on their success or failure in the history of science but instead applies a symmetrical analytical lens to all knowledge claims (Bloor 1991). 'Symmetry' is a tenet of the Strong Programme of scientific knowledge and, briefly, calls first for a recognition that both true and false beliefs need to be explained. Second, the causes of both true and false beliefs are of the same sort (Bloor 1973). Collective community consensus about the truth of knowledge claims is a social achievement. That different groups can derive similar claims independently involves agreeing on the correct rules, norms, tools and procedures to judge correctness. That these norms and tools will change over time helps to demonstrate that scientific knowledge is a social institution. The value

of scientific knowledge as objective, unbiased, and universal is instituted – made real – through collectives of people and things.

However, the recognition of science as a social institution does not undermine the importance of an agreed-upon set of collective methods and rules to conduct experiments. What needs explanation is *how* these norms and rules are made durable over time. The strength of any knowledge claim is linked to how far findings are agreed upon and shared among all members of a knowledge community. The most durable claims are those taken up by the largest group of supporters. The SSK concept of meaning finitism can illuminate this further. Bloor (1994) references Wittgenstein's writing on mathematical proof to show that a seemingly universal truth such as 2 + 2 = 4 is actually a system of concept application. This system is sustained through collective agreement about the meaning of the figures '2' and '4', and '+' and '='. The knowledge that 2, 4, and 6 should be followed by the number 8 is a convention that individuals must learn and then go on to sustain through future applications of the meaning of the terms 2, 4, 6, 8 and so on. It is not possible to know all future applications of the meaning of the concept '2' or the symbol '+' therefore the meaning of these concepts is finite.

There is nothing in the meaning of '2' as a concept, or its previous use that can fix its proper future use ad infinitum (Barnes, Bloor and Henry 1996: 78). Applied to the replication of scientific results, meaning finitism goes beyond insisting that experimental results are social conventions. For these proponents of SSK there is an insistence that the natural and the social are not separated and that one cannot be applied to explain the other in any straightforward way. Moreover, social conventions alone cannot explain the process of induction: 'For us, states of affairs in the physical environment have got to be taken into account to understand induction as a social process.' (Barnes, Bloor and Henry 1996: 76). It is not enough to highlight, for example, the way that scientific communities use norms and rules to classify a good experimental result from a bad experimental result. Analysts within SSK also recognise that states of affairs in physical environments produce locally contingent results, and it is the sustaining of the meaning of those results across time and space that forms the basis of understanding scientific knowledge as a social institution. These

insights help to inform my analysis in this thesis because the increased use of automation in experimental work requires the agreement of scientific communities that data produced using these methods remain acceptable over time.

For practising scientists then, efforts to understand the locally contingent aspects of the physical world run in parallel with efforts to reach collective agreement about what counts as acceptable and likely results among their knowledge communities. In practice many scientists, as I demonstrate below, recognise contradictions in these demands for reproducibility in experimental sciences. In the day-to-day concerns of addressing research questions and requirements of funded grant applications it is unsurprising that researchers do not often seek to repeat an already published experiment, or that journal editors will not accept new papers addressing the same experiment. There is therefore an expectation of the possibility of reproducibility in experimental sciences, even if this is not often actually put to the test (Casadevall and Fang 2010). To appreciate claims that the biosciences are currently undergoing a 'reproducibility crisis' it is necessary to examine how *expectations* for reproducibility are changing or not, and how the tools available to bioscience researchers may influence the ease with which these expectations can be put to the test.

Analysing expectations for reproducibility is beyond the scope of this present study, but my data in the following chapters demonstrates that automation does not significantly influence the ability to successfully reproduce experimental results. The main reason for this, I argue, is that it is the human operators that make the 'judgements of sameness' between one data set and the next, whether the data are produced using automation or not. As I will show in my case study sites, informants' decision to trust in their results was at best indifferent to the use of robots to gather the data, and often building trust involved intervening in the way the robot performed a task to make it more closely resemble the manual approach for that task.

A recent *Nature* survey of 1,576 researchers assessed the assumption of trust and integrity in published results. Reporting the findings of the survey, Baker (2016) highlights the number of researchers unable to reproduce others' experiments at 70% and over 50% have failed to reproduce their own experiments. Similar to Casadevall

and Fang (2010) above, however, because scientists trust the integrity of the journals, and recognise the precariousness of working at the edges of current understanding, only 31% of respondents believe this inability to reproduce results is a problem. There are indicators however that the academic community wants to improve '…the credibility of… published scientific literature…' (Munafò et al. 2017) by optimising elements of their scientific processes to promote reproduction.

One element of experimental processes that authors see as a target for optimisation is the ability to accurately dispense liquids. The need for 'reproducibility' in pipetting at small volumes or over large sample numbers requires 'considerable skill and practice… [and can be] …time-consuming, error prone, and tedious.' (Gaisford 2012: 328). Vendors offering automated liquid handling robots present researchers with solutions to a perceived lack of quality in current research practice. According to this narrative, the task of moving liquids around in performing experiments should not be left to human researchers alone, especially when automation tools now exist that can both improve the precision, efficiency and speed of experiments, at the same time as allowing results to be standardised and (at least in principle) to be reproduced by others in the field:

> … backers of automated labs say that the immediate pay-off of their work might be to promote a general movement to boost the overall quality of research. Tools that make it easy for scientists to monitor and record every aspect of their experiment[6], they say, might help to deal with what some argue is a 'reproducibility crisis' in research — the sense that many experiments are too sloppily done, or that methods and data are recorded too imprecisely, for others to easily reproduce findings. (Hayden 2014: 132)

However, Hayden's description of automated labs does not take into account how bioscientists garner trust and confidence in their results. Sloppy practices do surely introduce errors and mistakes but so do changes in temperature, oxygen, and pH levels (see chapters 5, 6 and 7 below). The scientists I have studied make judgements about

[6] See sections 4.6.1 and 4.6.2 below for analysis of potential implications associated with this approach.

good or bad results based on a combination of these influences. Precise recording and monitoring of every aspect of these influences, and every adjustment made in response would be at best impractical, and potentially unfeasible when you consider that judgments of sameness also involve 'interpretative flexibility' (Pinch and Bijker 1984). Furthermore, as I explore in the next section, as well as applying to experimental results, judgements of sameness also apply to acceptable tools for producing those results. I now turn to the concept of 'experimental space' and the policy and vendor promises for high-throughput technologies in the laboratory.

4.5.3 Experimental space and high-throughput technologies (HTT)

The phrase 'expansion of experimental space' does not refer to creating a larger laboratory room. According to policy and vendor accounts, there is an ever-widening scope of potential future biological research problems, and analysis of those problems will best be served by using automation tools. Experiments that are more complex are possible using automation in this view, and these technologies therefore promise to expand the experimental space of biosciences research. For over a decade policymakers and vendors have made the argument that IT systems and automation can expand the 'experimental space' for scientists in laboratories, in the form of 'high-throughput technologies' (HTT). The consultancy firm Faraday Partnerships produced a report commissioned by the Department for Trade and Industry (DTI) and the Engineering and Physical Sciences Research Council (EPSRC), entitled 'A Roadmap for High Throughput Technologies' (InsightFaraday 2004). Although the report does not contain a publication date, other sources indicate the roadmap was published in 2004 (Tolfree and Smith 2009). Originally taken up by large pharmaceutical companies for drug discovery, the roadmap authors cite HTT as having potential to revolutionise all investigative science:

> … high throughput methodologies… can readily be used as a tool in any investigative scientific programme. Use of automated experimentation releases highly skilled staff from "mundane" experimentation which would otherwise provide little opportunity for training or scientific or intellectual discovery. Some

> of these deliver the same type of benefit, e.g. improving the efficiency with which researchers can carry out routine experimentation and providing opportunities to explore a greater range of experimental space within the lifetime of a given project. This may provide opportunities to ask a wider range of "questions" within a given research project, or provide better quality data with which to test hypotheses or populate predictive models. Perhaps more importantly, the ability for experimental determination of a very large range of parameter space can provide a paradigm shift in the approach to a number of investigative science areas. (InsightFaraday 2004: 11)

One such area poised to take advantage of the expansion of experimental space provided by HTT and automation is synthetic biology:

> Automation of synthetic biology techniques will greatly increase the robustness of the processes and reproducibility of data collected. The net result will be an increase in the size of the experimental space covered by the investigator, and greater quality of the data and models produced. (Imperial-College-London 2015).

As the InsightFaraday (2004) report makes clear the use of HTT should now be understood as part of targeted or 'smart' analytics, and not a case of using brute processing force to identify processes or compounds of interest randomly. Rather, HTT allows laboratory users to pursue traditional hypothesis testing but radically increase the number of potential variables and cycles using high-throughput techniques on automated robotic platforms. It is this use of IT and automation for increasing the capacities of researchers in their experimental design that encompasses the clearest promise for the expansion of experimental space in laboratory automation. For example, if a researcher has a range of genetically modified yeast strains and each strain has a slightly different modification s/he might want to test the behaviour of each strain when mixed with similar growth medium. However, the research might want to also test, in parallel, how each strain behaves when mixed with different types of growth medium, or using different amounts of growth medium. By using high-throughput and multi-well plates, this researcher could map out potentially hundreds

of different combinations of strains and mediums and test those simultaneously. By using machine-learning combined with this high-throughput experimentation the researcher could potentially identify patterns and behaviours in yeast that would be difficult to achieve without these kinds of tools.

More than this, however, as outlined above, policymakers and vendors also argue that automation offers 'quality' improvements for data gathered using robotics and HTT. The double promise of coupling HTT and laboratory automation is therefore to increase the quantity of possible experimental data gathered, and raise the quality of that data through the increased precision and monitoring potential of these technologies. In the chapters that follow, I find users' experiences of automation at odds with this promise of rapid advances in the quantity and quality of experimental data. Despite these experiences, prominent researchers in the field of synthetic biology particularly remain committed to pushing forward with designing further automated tools and the associated commercial services of large-scale automation systems. I now turn to these kinds of business considerations in laboratory automation and synthetic biology.

4.5.4 The business of improving labs through outsourcing to robots

The majority of investment in developing laboratory automation and instrumentation tools globally is through commercial businesses and instrument manufacturers. In 2014 the list of top 25 instrumentation firms (based on sales totalling ~ $28 billion) included companies from the United States, Japan, Switzerland, Germany and the United Kingdom, with the United States dominating the list (Thayer 2015). The UK 2016 strategic plan for synthetic biology, the *Biodesign report* notes the success of the US in promoting synthetic biology start-ups through venture capital backed investment, and suggests the approach 'would be invaluable if mirrored in the UK' (SBLC 2016: 14). The number of US-based commercial outlets for laboratory automation is large and ranges from global corporations with long histories of producing scientific instrumentation such as Thermo Fisher Scientific, to relatively new start-up companies looking to be part of the above 'paradigm shift' toward fully automated laboratories, including 'cloud-lab' automation firms such as Transcriptic.

Transcriptic designed and set up its robot cloud laboratory facilities to address inefficiencies in molecular biological experimentation through fully automated, cloud-based protocols. A cloud-based service is one that offers customers online access to large robotic facilities, usually for a per-hour cost. The premise of Transcriptic is to make these large systems accessible to a greater number of researchers, and to reduce the time spent by researchers in biology on completing repetitive manual tasks; by using a robotic platform Transcriptic seek to 'drop the hands-on experimental time down to zero, or just a few clicks on [its] website' (Transcriptic 2017). Transcriptic based its model on an outsourcing of parts of molecular biology experimental protocols that customers would have previously undertaken within their own laboratory in academia or industry.

An alternative to robot cloud-based outsourcing is for labs to purchase their own desktop robots. Companies are now designing and marketing smaller liquid handling robots to sit alongside existing instruments on the laboratory bench. Current desktop robots include Analytik Jena's GeneTheatre, OpenTrons' Kickstarter-funded OT-One, and the Andrew Alliance pipetting robot. The GeneTheatre and OT-One are similar in that they both operate on a gantry system, which means they operate using pipetting heads that have the capability to pipette liquid through one or more tips at any one time, moving above a bed of plate decks housed in a cube-like set-up. The Andrew Alliance vendors marketed their product as a desktop pipetting robot, but differs from this cube-like box design and uses robot arms to move a series of standard single channel pipettes, identical to those used by researchers in the lab. The Andrew Alliance uses a series of cameras and sensors to detect liquid levels and well positions and is sold as an extension of current manual laboratory methods but with far higher levels of precision, and the ability to record each stage of the experiment for improved productivity and analysis (RBR 2014).

There are competing claims about the relative benefits of outsourcing to robotic cloud-based labs or purchasing desktop robots for individual labs. Automation advocates in synthetic biology view robots as inevitable next steps in improving the way that current laboratory bench science is practiced (Weldon 2013, Rawat 2014, Spencer 2015). These improvements include, for cloud-based services, reducing the amount of waiting

biologists currently experience as different stages of an experiment are set up and completed, or, using desktop robots, a standardising of protocols and the removal of 'all ambiguity' when troubleshooting experiments (Spencer 2015). This reference to reducing ambiguity is implicitly positioning a human tendency to deviate from a set protocol as the source of 'all ambiguity'; however, as my data in Chapters 5, 6, and 7 shows, ambiguity can come just as easily from the automation platforms researchers are building. For cloud-based services in particular there seems to be a further stated aim of opening up scientific experimentation to a wider range of users, sometimes labelled a 'democratisation' of the biosciences (Bates et al. 2017). However, groups will still need to pay for services, so democratising in this case is for people with considerable amounts of money.

Promissory advocates of automated workflows in synthetic biology have also raised doubts about the need for so-called anthropomorphic robot designs that mimic the behaviours of current laboratory users. These systems, such as Maholo LabDroids (Yachie and Natsume 2017), are attempting to automate the scientists' individual practices rather than creating the most efficient way to complete an existing process (be that automating a manual approach or redesigning the approach to fit better with computer science tools). For McClymont and Freemont (2017) the automation of laboratories brings down the cost of the hardware, and is not there to develop anthropomorphic systems that mimic individual scientists at the bench. However, as demonstrated in Chapters 6 and 7, judging how well-established laboratory automation is, and defining 'efficient science' must include considering how users build trust and confidence in the results gathered from their own specific system. For users in my case studies, having confidence in the robot, especially when 'troubleshooting', comes from thinking through how the users might create the right conditions for a successful experiment. While the robot's movements are not anthropomorphic as such, the criteria for judging the robot as functioning successfully is very much human-shaped. Consider the way that researchers in the next three chapters begin to trust the results derived from their platforms: these researchers look at, feel for, and talk about those results with their colleagues. No leaps in understanding can come without those bodily intuitions, group memberships and communal agreements.

The second part of this chapter looks at examples of other computer programming approaches to making changes to laboratory practices. By comparing how different practitioners are trying out alternative approaches to solving problems they see in the biosciences, part two of the chapter shows that pursuing automation and robot platforms as critical to the future of the biosciences is a choice. The radical future value of automation for the biosciences is by no means a consensus.

4.6 Part Two: Robots not included – alternative IT interventions in the laboratory

> So the thinking is that we can solve a lot of the problems by taking the human out of the loop. But that's not the right approach either. Biology is not computer science. …. My argument is that we don't need an automated lab. We need a *smart* lab, one in which the human being is optimized, not replaced. (Martin 2016)

There are alternative applications for information technology (IT) in biosciences laboratories that do not include using automation hardware such as robotics. These systems do not use automation to mimic the behaviours of current laboratory users; rather they use a combination of digitisation, learning algorithms and sensors to *change* the behaviour of individual users. Currently the promotion of so-called 'smart labs' is most visible in the United States. The two examples below are from an academic research laboratory at the University of Washington, and a Massachusetts Institute for Technology (MIT) backed start-up founded by ex-employees from MIT, Imperial College London, and Gingko Bioworks.

4.6.1 Standardising through sharing and surveillance

The Eric Klavins laboratory at the University of Washington, Seattle had developed a system for using computing technologies to standardise laboratory protocols. The system, named Aquarium was developed out of a sense of impatience by Klavins and his team to move towards standardised protocols and robotic platforms, even as providers of such platforms 'were not yet ready for [the things Klavins' team wanted to do]' (Klavins 2015). For example Klavins (2015) described how PhD researchers in his laboratory have attempted to use providers of large cloud-based robotic platform

systems, such as Transcriptic, but so far the results have been ‘clunky’ at best. Part of the explanation for this, he argues, could be that large robot platforms currently optimise protocols for a limited number of research areas (e.g. making small compounds using yeast). Therefore, in the meantime as these systems become more widely useful, researchers might instead require a system like Aquarium. This is because the Aquarium team promotes its system as capable of working in any laboratory. It claims that Aquarium acts as an ‘operating system’ for any laboratory, exchanging information and instructions across an abstraction barrier between experts and novices to execute experimental protocols.

One example of how Aquarium works is that experts such as postdoctoral researchers develop experimental protocols in the first instance. This protocol is then encoded into ‘krill,’ a computer language for semi-formal protocol descriptions (Klavins 2015). Researchers then share the coding and protocols on GitHub, an online repository for sharing code among a community of programmers. Other researchers can then access the code and test the protocols. Each user develops a profile highlighting the number of contributions they have made to others’ designs which amounts to a form of rating available to future designers deciding whether or not to accept suggested changes sent by an unknown developer (Finley 2012). GitHub allows version control and change tracking as users develop the protocols over time. Part of this ongoing improvement takes place through presenting protocols to technicians in the laboratory via touch screen monitors with the technicians following step-by-step instructions. The success or failure of the protocol is monitored over time and those with a low percentage success rate will be reviewed and revised (Klavins 2015).

The Klavins laboratory created Aquarium in partnership with the Intel Science and Technology Centre for Pervasive Computing (ISTC). The ISTC commitment to ‘pervasive computing’ continues the work of ‘ubiquitous computing’ of the 1990s / early 2000s. With connections to work on creating ‘computer walls’ at the Xerox Palo Alto Research Centre in the 1980s the idea of ubiquitous computing was conceived as a way to universally connect a system of computers that would be spread universally ‘… but invisibly, throughout the environment.’ (Weiser, Gold and Brown 1999: 693) One way the ISTC helped develop the Aquarium system was through ‘activity

tracking': tracing the movement of all objects and people within the laboratory through motion sensing cameras (Aquarium 2014). Therefore, in addition to protocol-sharing using GitHub the Aquarium system also has sophisticated monitoring techniques at the laboratory bench. These monitoring features allow users to assess protocols according to success rates, with this data then being fed back into the system in a continual iterative process of improvement for streamlining and efficiency.

The main finding Klavins highlights from the redesign of his laboratory space and installing the Aquarium 'operating system' is that by making the designers (experts) of protocols hand their instructions over to entry-level technicians (via krill and steps in the Aquarium architecture) the laboratory's work has collectively become more reproducible (Klavins 2015). There have been challenges however in implementing this system, especially for non-entry-level laboratory employees: reflecting on the first year of using Aquarium the Klavins Lab states 'Initially, not everyone in the laboratory wanted to use the system. They had to put all of their samples into the inventory management system, they had to give up control over their own Gibson assemblies, they had to learn a new system.' (Aquarium 2015). The Klavins Lab envisaged this new system as a learning tool for teaching non-experts to work in a standardised way and to eradicate any non-standardised practices for expert designers of laboratory protocols.

Importantly, at the time of writing, Klavins and his team were pursuing standardised, reproducible science without significant input from laboratory robotics. The focus on standardisation without robotics also shows that the expectations for the future of the biosciences as more reproducible is about more than a problem with human error in pipetting. Klavins' approach to using surveillance on all aspects of his laboratory's routines demonstrates that successful experimentation in the biosciences is about judgements of correctness across a whole range of activities in the laboratory. My data suggests that even this level of surveillance cannot capture everything that makes up a proper functioning experimental system, and that 'attentively engaged' amphibious practitioners are essential to this process

4.6.2 Augmentation not automation

One of the emerging narratives surrounding the application of computer science tools to biological research problems is the need for human augmentation, rather than wholesale automation. In addition to the kind of multi-disciplinary training highlighted in section 4.5.1 above, advocates of human augmentation envisage melding computer science and biology into a single discipline with an expectation that in the future all laboratories will be 'smart labs' (Martin 2016). Based in Boston, Massachusetts, BioBright is a company looking to build tools to augment scientists and '… revolutionize the way biological research is done … without disrupting scientific workflows…' (BioBright 2017). BioBright argue that their systems enable augmentation by creating connectivity between instruments, using software to automatically store and retrieve data, and sharing experimental data between scientists on a cloud platform:

> [BioBright] built a voice assistant called Darwin tailored to recognize biomedical research terms, and software that automatically collects data from laboratory equipment. Information is recorded, aggregated, and analyzed in the cloud where other scientists can access this integrated record in order to duplicate the experiment. (Brown 2016)

Importantly, for the people behind BioBright, current laboratory users can integrate their software and instruments capable of recording and sharing data without the need for robot platforms. The key to solving the reproducibility crisis (see section 4.5.2 above), for BioBright CEO Charles Fracchia is communication between scientists and the ability to replicate workflows: '… most reproducibility problems stem from translating workflow between researchers. "Automation won't help with that," … "BioBright's human augmentation, however, allows the scientist to say "Darwin, show me the average temperature that I've used for the last three months, or show me how Mike did it last week."' (Brown 2016). Here the BioBright assertion is that smart labs can help capture some of the 'tacit knowledge' (see Chapter 2) that researchers translating workflows require to do this effectively.

The problems to be solved for BioBright are less about using robotics to improve the precision of experimental practice; rather they promise to use integrated software and algorithms to help scientists recognise fluctuations in protocols automatically as they happen, and to share others' data and protocols via online cloud platforms, enabling greater standardisation and reproducibility. As my data suggests in Chapters 6 and 7, increasing the ease with which researchers can share protocols will only influence judgements of correctness if the results are in line with the expected outcomes of the experiments for different groups. Cloud-labs on their own will not help with reproducibility in this case.

There are a number of barriers to realising the benefits of smart labs identified by Fracchia, including the use of notebooks in the laboratory. Using a handwritten notebook to develop a protocol relies on the accurate recording of information by scientists as measurements are taken (which with gloved hands can take place some minutes after readings have been observed) (Brown 2016). The use of individual paper notebooks also creates numerous records of experimental setup conditions that are not available to other scientists that may be working in a related area, or who may benefit from not repeating the errors found by previous completed work. Advocates of smart laboratories argue that humans are limited in their potential to retain and record information, which bears similarity to automation advocates' arguments that human error is the main cause of non-reproducible experiments. However, the difference between smart and automated laboratories is that smart laboratories aim to measure and share the outputs of the experiment more rapidly than would be possible for a person. Liquid handling robot advocates want to replace the way inputs enter the experiment.

In either case, it is important to think about why researchers use handwritten notebooks or prefer to complete a task at their own bench, using their own tools. I argue that researchers' sense of who they are and their identities as competent researchers are connected to these preferences. Furthermore, researchers' trust and confidence in others' results are equally connected to how well those results fit with the expectations of their communities of peers. My analysis of data in Chapter 6 below explores how users gain trust and confidence in theirs and others' results. Often, researchers did not

see the use of automation as a solution to these problems of reproducibility but rather they incorporated the strengths and weaknesses of automation tools, and intuitions about correct functioning, into existing rituals of knowledge exchange and debates about good and bad data.

Another way to think about this however is that experimental results are intellectually and commercially valuable and sharing may not be the first instinct for a group that wants to take advantage of the work they have put in. For Fracchia the solution to reproducibility and credibility issues in the biosciences will not be found by replacing humans in the laboratory but by providing software and connectivity that allows humans to track and share their experiments more easily using the power of computer science. In this view, Fracchia and his team see science as a culmination of idea sharing that can be better organised using computer science to augment human abilities to remember and classify information. My data suggest computer science benefits for the biosciences are directly related to the skilled practitioners that can make those tools work for their particular experimental goals.

4.7 Conclusion

In this chapter, I have explored various policy promises for automation and synthetic biology. I have described my initial interest in the efforts to introduce standardisation into these areas, and I have presented alternative options that machine makers, policy writers and practitioners have put forward for improving biosciences practice. The first part of the chapter examined the UK's synthetic biology strategies for implementing large-scale automation facilities. Policymakers viewed automation and synthetic biology as a natural partnership that would advance the biosciences by improving reproducibility of experiments, increasing the processing power for large-scale experiments, and boosting the UK economy by promoting investment in products and services. The second part of the chapter showed that several alternative visions exist that aim to solve the same issues that automation advocates say their platforms will solve for biosciences researchers. Importantly, despite synthetic biology's stated ambitions of importing engineering principles and practices into biology, the need for standardisation to do good experimental work remains unproven. However, I note that notions of a crisis of reproducibility in science are also economically useful to

companies like BioBright. For some scientists in my initial pilot work below, science has progressed well to date without specific standards that underpin reproducibility. I view the timing of fervent calls for addressing a reproducibility crisis in the context of a host of new companies set to derive financial benefits from talk of a reproducibility crisis taking hold in UK academia.

In the next chapter, I begin to analyse empirical observations in this area. My experiences of talking to and observing prominent researchers in the field of synthetic biology demonstrated that the policy promises for automation were still very much anticipatory. I now turn to the first of these observations and draw attention to competing priorities and ambivalences among leading practitioners in the areas of laboratory automation and synthetic biology.

CHAPTER 5:

Practitioner narratives: ‘new paradigms’ and ‘mothering mode’

5.1 Introduction

This chapter describes and analyses my observations from attending two practitioner workshops. The first workshop, held in early 2015, was a joint European Union (EU) and United States (US) event focused on standards in synthetic biology. The second event was an industry and academia workshop on automation in synthetic biology. It was during the first EU-US workshop on standards that I decided to reorientate my empirical research towards automation in the biosciences. The second workshop was held in early 2016 and I took a break from my ethnographic fieldwork at Case Study 1 to attend the event and hear about automation and synthetic biology. My experience at the industry-academia workshop in early 2016 helped to re-emphasise what I was noting in my fieldwork: that many different types of automation tools are available and that practitioners are far from unified in their views on how laboratory automation will be influential in the biosciences and in synthetic biology particularly. Both workshops provided important ethnographic moments and flashes of insight that helped shape the direction of subsequent research and analysis. This chapter offers details of those insights, and how certain discussions between practitioners provoked further lines of enquiry for my study. To contextualise the importance of some of those insights for the thesis, it is necessary in this chapter to preview some of my later fieldwork.

Having analysed the promissory narratives about automation and synthetic biology found in policy documents, I was keen to listen to and speak to practitioners working in areas of overlap between the two areas. My analysis of practitioners’ presentation slides and formal talks shows that many prominent researchers in synthetic biology view both standardisation and automation as important topics. However, no consensus yet exists as to the way bioscience researchers can best pursue standards or utilise automation. This chapter presents some of those various positions and begins to connect the ways in which different proponents of various automation tools make

distinctions between theirs and others' work in the area. The debates I observed were not just differences of preferences for particular tools. Rather, some of the material used in presentations and arguments raised in discussions centred on fundamental differences in (a) the necessity of standards for the biosciences, and (b) the definition of what counts as 'real' laboratory automation. These debates are unpacked in this chapter using the future value of technology literature and the identity and methods literature discussed previously in Chapter 2.

Some of what I heard from listening to practitioners during presentations was a restatement of the promises made for automation and the biosciences outlined in Chapter 4. However, I also paid attention to talk about automation and the biosciences outside of the formal presentations, during coffee and meal breaks, and during more informal question and answer sessions. Importantly, I compared both formal and informal talk about automation and synthetic biology to my initial experiences observing practitioners in laboratories who were attempting to use and develop these tools. To try and make sense of how talk and practices compared, I held one-to-one informal discussions with different attendees at the industry-academia workshop in early 2016. One of those attendees, Peter, had previously worked in the UK academic biosciences and now helped to run a commercial laboratory automation vendor based in Germany. Initial conversations with Peter sparked further questions that I then followed up during a Skype interview in the months following the workshop. As I discuss below, Peter's insights into industry and academia views on high-throughput versus low-throughput robot platforms contributed to my later thinking on speed and efficiency, experimental space and reproducibility.

5.2 Aims of the chapter

The main aim of this chapter is to demonstrate the multifarious nature of promises about the future value of automation and synthetic biology. There is no simple unified set of promises that all vendors and policymakers agree upon when considering automation and the biosciences. One of my aims in this chapter is to make this point clear because when reviewing specific policy documents such as the 'Biodesign for the Bioeconomy' strategic plan, it can be tempting to assume that researchers agree about how best to proceed. The *Biodesign report's* description of the need for further

adoption of 'non-sophisticated' automation technologies is a clear example of this, because, as this chapter will demonstrate, defining sophistication is relative to the types of problems and solutions with which each group is working with. Indeed, some of the most seemingly simple tasks held up as non-sophisticated in the *Biodesign report* are actually incredibly difficult tasks to complete using automation, and different laboratory automation specialists will see the role of automation differently according to the particular arrangements of their workflows. In this Chapter, I review debates about the place of automation in scientific workflows – that is, the preferred order in which different bioscience researchers chose to organise their experimental work – and conduct textual analysis of presentation slides. Both the debates and the slides are evidence of a disparity of views ranging from seeing automation as a radical departure from existing laboratory practices to regarding it as part of an evolving set of tools which researchers can simply integrate into existing ways of conducting experimental work in the biosciences.

5.3 Structure of the chapter

To help meet the aims above, I have organised the chapter in to three parts. The first section is an ethnographic account of my time at the EU-US workshop on standards in synthetic biology. The account includes descriptions of the content of speakers' presentations as well as observations made during question and answer sessions between formal talks. The second part of the chapter similarly provides details of some of the observations I made during the industry-academia workshop on automation and synthetic biology. In this part of the chapter, I review presenters' slides and reflect on how they presented automation differently depending on their disciplinary associations. The final part of the chapter provides an analysis of the interview with Peter, the automation specialist who attended the workshop and discussed low-throughput robotics during our initial conversations. The analysis of this interview provides a framework for comparing some of the radical claims made by a number of other automation proponents at the workshop, and it also shows that talk about 'paradigm shifts' enabled by automation remains rhetorical for the majority of current practitioners in the field.

5.4 EU-US stakeholders workshop on standardisation in synthetic biology

Over three days in early 2015, framed by the clear blue skies of a medium-sized Spanish city, I listened to some of the major proponents of synthetic biology discuss the merits of, and challenges to, standardisation in the field. As section 4.4 described above, standardisation was a founding objective of the field for some of the early proponents of synthetic biology. In the decade or so since these first publications, research funding bodies have supported a number of projects aiming to promote standardisation in the field. The EU-US workshop was a final event for one such project and I agreed to attend and to act as a note-taker for the two-day workshop. As note-taker, I remained in the room during all of the sessions over the two-days, including all question and answer sessions. I also made my own notes during coffee and meal breaks and it is these notes that form the basis of this episode. One of my strongest first impressions of the event was the number of attendees from different backgrounds, including differing academic disciplines, research funding bodies, and commercial biotechnology companies in the US.

Reviewing my notes after the event, I noted a tension between different speakers' perspectives on the importance of standardisation. The group at the workshop consisted of mainly senior level academics, including professors and principal investigators from European and US universities, as well as a smaller number of senior representatives from US and European commercial businesses. These businesses had links to academic concerns in synthetic biology, including biofuels and antibiotic manufacturing techniques. I did note a consistent view among the majority of attendees that they needed to apply systematic engineering approaches to biological research. However, through close analysis of how different attendees talked about engineering approaches it became clear that 'systemisation' and 'engineering' had diverse interpretations. For example, one group of researchers viewed engineering standards as essential for increasing reproducibility in biosciences research, whereas, for a different group, no such engineering standards had been required in the biosciences to date. In this other group, most scientists agreed that experiments had

been reproducible without a common set of explicit engineering standards similar to the type they were discussing at the meeting.

Furthermore, one presentation emphasised the essential role for standards when using information technologies (IT). This presenter described how researchers are using IT tools to design, build and test complex biological systems. The way the presenter spoke about their platform suggested that it relied upon the creation of standard measures for the characterisation of biological parts and devices. Characterisation, as discussed in section 4.4 above, involves understanding how different users may want to use a biological part. The speaker outlined a further objective for the platform arguing that automation would help create large, comparable datasets that allowed for compatible design information. This conception of data produced through using automation tools focused on how automation can organise and systematise the way researchers present their data, hopefully allowing different researchers to use different systems to produce compatible data. Once data sets are comparable, according to this speaker, different researchers can use different systems to work toward similar research goals because the datasets are standardised enough to allow collaboration on the design of future experimental work. As my data below shows, comparisons of datasets involves user interpretation and, although automation could facilitate this within the same system and among close collaborators, sharing between institutions with different setups and varying goals involves considerations beyond just the technical capacities and setup of the platform and software.

This brings me to another important discussion that took place during a question and answer (Q&A) session at the workshop. One of the workshop leaders posed the question, ‘what is stopping the community adopting each other’s standards rather than creating their own?’ One of the answers posed was reproducibility; that is, practitioners need information systems to systematically collect, record and disseminate information that is reproducible across time and space. However, as one attendee remarked, ‘the behaviour of most practising scientists is that they don’t care about reproducibility.’ He went on to say that, they care about getting something to work (and journals care about reproducibility in the context of peer review) but in their day-to-day practice most scientists do not think about other people being able to

reproduce their work at a different time and place. A different attendee's response to this view was that reproducibility is a philosophical foundation for science and to say science needs standards for reproduction is to undermine this position. The attendee was arguing that scientific knowledge has been reproducible throughout history without a set of standards as conceived of by the previous speaker.

This exchange summarises the tension explored in section 4.5.2 above about collective agreement on what counts as the right result, and the right method. For the first attendee in this exchange, researchers needed to make formal standards explicit to apply engineering design to biology, while for the second attendee no such formalisation has been necessary so far in the history of the biosciences. These debates helped in the development of my first two research questions relating to promissory narratives, lived experiences and identities (RQ1 and RQ2 above), because attendees at this workshop used their own experiences and understanding of what the terms 'science' and 'engineering' mean to identify with different saliencies in those areas. They also expressed commitments to different ideas of proper scientific practice. In doing so, they reinforced their sense of belonging to groups of researchers that either did or did not see standards as important for scientific practice.

It was during the summing up session on the first full day that attendees were asked if there were strong feelings about what cannot be standardised; 'human beings' was the first response, eliciting laughter from the rest of the group. It was at this point, having listened to several speakers debate the power and potential of laboratory automation that I could see what those speakers would say the intuitive next step would be for solving this standardisation problem: reduce human input and increase the use of robots in the laboratory. My writing-up and refection on this episode formed one of the 'ethnographic moments' in the study. I understood that in the use of humour about standardised humans, researchers were conflicted in their choices about the role of automation in synthetic biology. For many in the room there seemed to be a belief in the power of automation tools for potentially enhancing their work. Equally, however, some of those same researchers had spent many years working in the field and had developed a scepticism about so-called revolutionary changes in approach, especially considering the kinds of work that are seen as valuable in the biosciences.

A clear example of the potential value of automation came from one speaker's presentation about the two-sided nature of conducting experiments in synthetic biology. The presenter divided his talk into two versions of experimental design in synthetic biology. The first half provided a description of experimental processes that researchers could design and calibrate using predictive modelling. The second half of the talk looked at researchers using automation and robotics to understand how they could activate certain model proteins in an operon, which briefly, is a set of promoter sequences and operator sequences that control transcription of a gene (Scitable, 2014). There was initial optimism as researchers designed their processes and envisaged a relatively straightforward engineering project. However, out of the eleven original proteins, researchers deemed nine inappropriate for various reasons, including incompatibility with automation processes. Of the two remaining proteins, one required use in highly non-diluted form and the other required significant further research and development to determine its activity.

In conclusion, the speaker estimated that it would take five years and two PhD students to answer this seemingly simple modelling hypothesis for the activity of a protein in an operon. This summary suggested that even simple engineering in biology was susceptible to failure and most attempts at such biological engineering remained significant research projects. He commented, 'there are many things we can fix in biology, given enough time and money, but there are very few things that work at the level as an engineer selects a screw'. This presentation was a deconstruction of the failure of engineering with biology. He talked through the simplicity of the premise behind what should be possible, before demonstrating from experience that the field is a long way off engineering even simple mechanisms, with a great deal of time and money required to do so. Tellingly, the speaker commented that this type of work is not exactly 'Nobel worthy,' and therefore dedicating such resources to these ends would not make a great deal of sense for current research leaders in his area.

My experiences at the EU-US workshop emphasised that the topic of standardisation in synthetic biology divided opinion among leaders in the field. Perhaps most significantly, as the presenter above made clear, some prominent synthetic biologists

felt that the work required for creating standards was an impossibly large and intellectually questionable task given current resources and funder research priorities.

I now move forward approximately 11 months to describe my observations and interviews at the industry-academia workshop held in early 2016.

5.5 Industry and academia workshop 'automation and synthetic biology'

By the time the organisers held the industry-academia workshop in early 2016, I had already spent six months observing the work of the Rhodes Lab (RL) (see Chapter 6). The workshop was in the same institute as the RL and the location and venue for the workshop was in a section of the building I passed each day on my way for morning coffee. The organisers of the workshop stated that their motivation for the event was to bring together commercial automation specialists with bioscience researchers in academia. One focus of the workshop was on how automation tools might allow researchers to scale-up their research. For processes utilising synthetic biology and genetic modification to produce compounds of value, researchers first need to find out if it is possible to use such synthetic biology techniques to create the compound. Once researchers have completed this initial 'proof of concept,' they may wish to scale-up the production process so that a method can be utilised to ensure that the quantity of compound they produce is large enough to justify commercial investment. A prominent example of the importance of scale-up in synthetic biology is the production of the compound 'artemisinin,' an active ingredient in anti-malarial drugs (Shretta and Yadav 2012, Paddon and Keasling 2014).

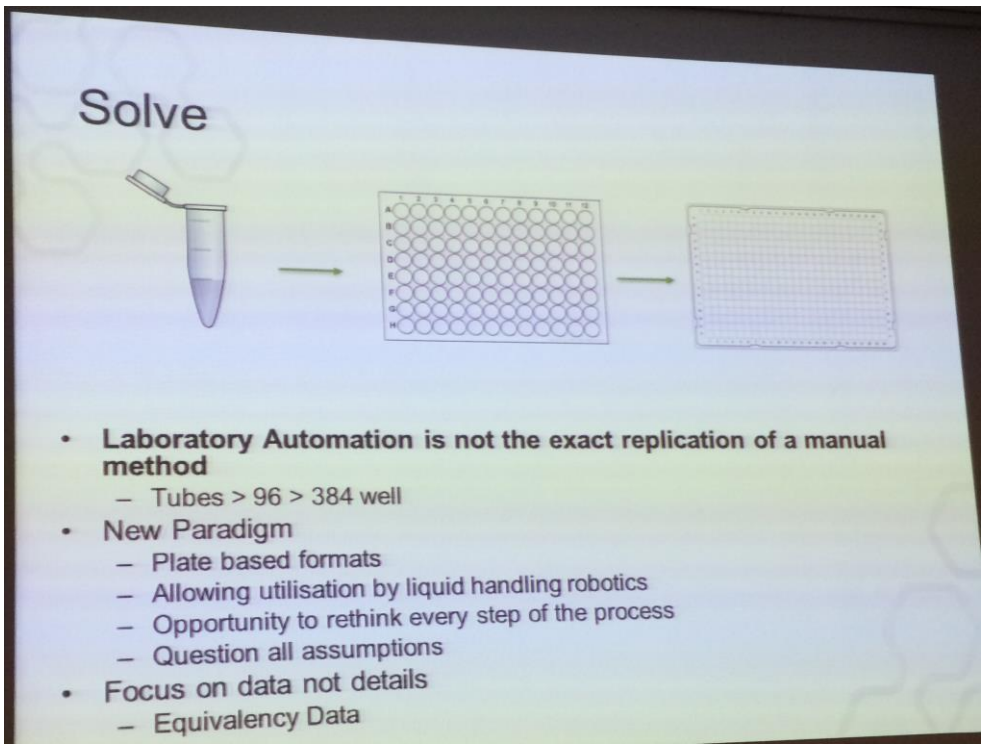
On the first day of the industry-academia workshop, I walked down the stairs to join the crowds of new arrivals in the central space, collect my name badge, and programme agenda for the two-day event. My fellow workshop attendees were a mix of familiar faces from the host institution and others I had visited during my research. Additionally, attendees included academics from several other UK universities, and a significant number of representatives from instrument-makers and commercial service providers, many promoting laboratory automation products and services on offer for

purchase. As I greeted colleagues and made introductions, I thought about the echoes of our voices drifting up as an indecipherable hum to the rest of the building occupants. Would our event be a distraction from their work as they tried to make sense of pages of experimental data on their screens? Alternatively, would the buzz of the crowd below generate intrigue and excitement for these researchers, keen to understand what partnerships with industry could open up, and the tools of automation provide?

The event organisers divided the day into sessions of formal presentations and sessions of facilitated group work. The presentations during the first day included those by several large DNA synthesis companies and academic research centres with DNA synthesis capabilities. One research centre presentation was particularly striking for my purposes because it clearly positioned developments in laboratory automation as a 'new paradigm' in the biosciences, a change that required researchers to 'question all assumptions' (see Figure 2 below). My time at the RL to date had been full of difficulties in translating existing laboratory bench procedures on to automated platforms. For the most part however, my informants at RL regarded their automation platform as additional to the more traditional wet-lab facilities available. As the next chapter makes clear, the RL could not function without access to both.

I now turn to examples of how certain proponents at the workshop viewed automation as a radical break – a paradigm shift – in the practice of experimental work.

Figure 2: Laboratory automation as 'new paradigm'



The presenters promoting a new paradigm picked a point of departure as the shift from tubes to microtiter plates. For this group of researchers, going from individual tubes to 96 well and then 384 well plates, allows users to rethink every step of their processes. Having spent the last several months in the RL, I was struck by the proposed separation of tubes from plates in this presentation. As I outline in the next chapter, in the observations and conversations at the RL the use of tubes and hand-held pipettes was still very much part of the team's process for developing their understanding and working with the robot platform. Indeed, it was often through testing certain mixtures and reactions using the tubes and single barrel pipettes that the RL team could gain confidence in the results coming from their analyses using the robot platform and the microtiter plates. I was left wondering if my particular site was in some ways unique in that approach to using both tubes and plates. After subsequent conversations with Peter later in the workshop, I understood that many researchers remained committed to using automation as a tool to enhance their existing approaches rather than an

entirely new set of practices to replace previous ways of working at the laboratory bench.

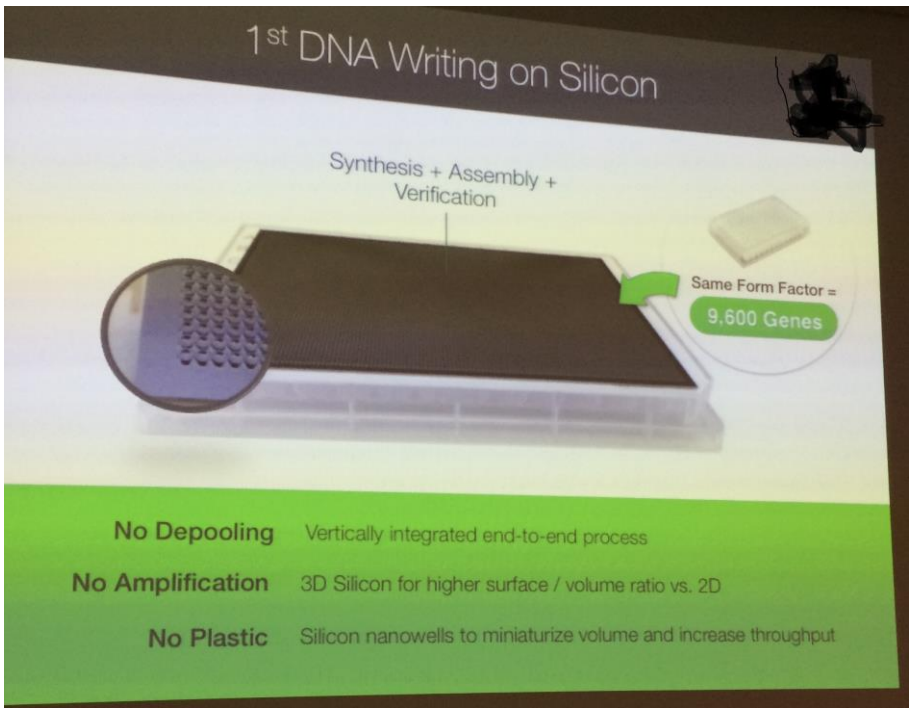
My data in subsequent chapters supports the view that there can be no clean break between bench-based and more automated approaches. Moreover, there is an inherent tension in constructing radical difference between robot and manual methods because system builders are often people with extensive bench experience. These users will undertake experiments following their knowledge of how to succeed at the bench, and think about the ways they can use automation to replicate or improve upon those approaches. I became increasingly convinced that laboratory automation may not be designed to exactly replicate manual methods but that laboratory users' engagement with automation must begin with ideas about what counts as a good method and the right result. Those automation specialists employed to make automation systems work in the biosciences were the amphibious researchers I met during my case studies (see Chapters 6 and 7 below).

The PIs at my case study sites hired amphibious researchers because of their knowledge of computer software and hardware and their knowledge of such tools in the context of biological research. However, users chose to be committed to the value of those tools because of their ability to utilise the tools to generate research findings and experimental results that chimed with other findings within their knowledge communities. These amphibious researchers generated that trust and confidence by using their embodied tacit knowledge of how to conduct good laboratory practice and applying that thinking to judge the good and bad behaviours of their robot systems. The fact that vendors are not designing robots to be anthropomorphic or to replicate human actions does not significantly affect that process of building trust and confidence in robot behaviour. Amphibious researchers rely on a legacy of human actions deemed to be right for conducting good experiments and draw from those legacies to define what counts as correct experimental practice.

One of the more difficult questions to answer was how researchers could translate these ideals of good experimental practice to increasingly smaller plate and sample

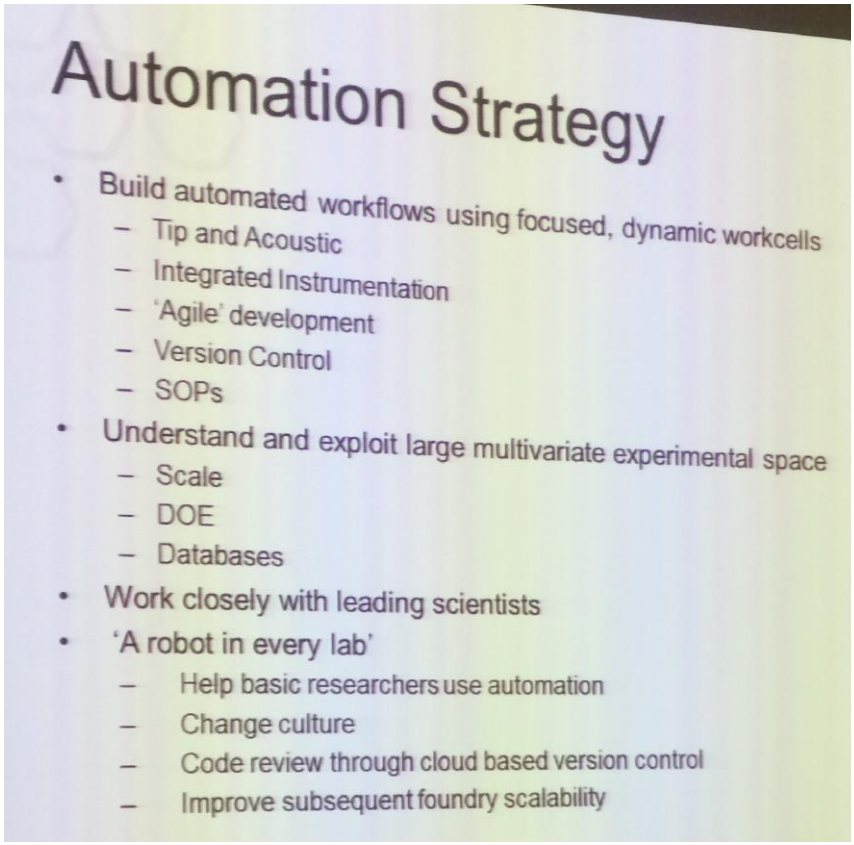
sizes. For one group presenting at the workshop even 96 and 384 well plates would eventually be replaced by silicone chips (see Figure 3 below). This large cloud-lab service based in the US promoted a chip with over 9000 individual wells able to mix liquids at the nanoscale. This presentation caused some other speakers to comment and to compare the use of nanoscale chip DNA synthesis with their own work, often with humour and an implicit assumption that the chip is the future in this area. However, as this and the following chapters demonstrate, there are complex reasons why researchers choose certain tools over others. My data for example highlights that flexibility and the ability to adapt experiments was a key motivation for researchers using both traditional wet lab bench techniques alongside their automation platforms. In each of these movements back and forth between approaches, researchers want to be able to switch between each method and in doing so they gain confidence in how the tubes, plates, and chips can be utilised best for different purposes. One method does not replace the other in any straightforward way. Each method, tube, plate or chip, has an appropriate application. Furthermore, promoters of low-throughput techniques, as explored below, are targeting the tube using market, which remains large in UK academic settings perhaps because of the flexibility it provides for researchers who want to adapt and change how they complete their work using different methods.

Figure 3: Silicone chip DNA assembly



For the research teams hailing a paradigm shift in the use of laboratory automation, they are mainly referring to high-throughput techniques. The definition of high-throughput, as the previous chapter described, is the ability to simultaneously conduct and analyse huge numbers of experimental variables in parallel. Researchers refer to this conception of potential variables and problem-solutions as 'experimental space.' It is important to note that, in the instances I discuss below, experimental space is an abstract conceptual entity made up of possible data points, parameters and experimental designs with which researchers are working. Proponents of high-throughput laboratory automation believe that they can expand the parameters of possible experimental designs by increasing the possible number of variables that they can test in parallel. More than this, computing power can help to analyse these variables quickly and enable researchers to use powerful computer processers to find patterns and linkages between many thousands of data points. It is this application of computing power that high-throughput advocates say will enable an expansion of experimental space by robots and automation in the biosciences.

Figure 4: Experimental space and 'a robot in every lab'



As well as enabling an expansion of experimental space, presenters advocating high-throughput robots also called for an increase in the numbers of researchers using robots in their day-to-day work. The presenter advocated a change in culture so that basic researchers could use automation. Having a 'robot in every lab' (see Figure 4 above) was the speaker's ambition. There were echoes of the *Biodesign for the Bioeconomy report* authors' call for cultural assimilation in this sentiment. The large specialist automation centre presenting at this workshop had previously helped to distribute small desk-based liquid-handling robots to other laboratories at their own university. The hope was that researchers in these other labs would begin to try out their experiments on these bench top liquid-handlers. If they could not get their protocols to work, it was no major loss except the person's time conducting the trial. However, for protocols that did work the automation advocates could feed that data back to the central facility and contribute to a library of protocols they could use again in future.

Later on it was fascinating to think again about this account of generating interest in laboratory automation by distributing small desktop robots to more traditional wet-labs in the institute to create protocol libraries. In Chapter 7 below, I describe my discussion with the software manager at the AL case study site about creating central repositories of standard protocols. In brief, this discussion emphasised how well the AL team needed to label these libraries of functions for the protocols to be of future use. I compared my AL observations to the above presenter's account, and it was not clear to me how closely users of the bench top robots worked with the large facility in order to ensure they were working with similar nomenclature. Based on my empirical work it seems highly likely that distributing the desktop robots out to laboratories would be one part of larger process to collaborate with those new automation users to understand how they were using the machines and for what purposes. The central collation of a library of protocols gleaned from other laboratories would be useful as far as future users could understand the labelling and context dependencies of those protocols

A further ambition for presenters at the industry-academia workshop was that laboratory automation would allow users to rethink every step of their processes. The use of multi-well plates over tubes opens up the laboratory to liquid-handling robots, and one presenter emphasised that for the researchers in his research centre the robots were there to allow users to focus on the data, not the details and methodologies of how they recorded and collated that data. Several large synthesis companies repeated this argument, including the US-based cloud lab service provider described above. As mentioned, this company presented arguments for the benefits of completing DNA assembly at the nanoscale using silicone chips rather than the current plastic 96 or 384 microliter plates favoured by robotics platform users (see Figure 3 above). It was difficult to reconcile such vendor positions 'that the data is all that matters' with my later empirical work, especially because in my case studies judgements of data quality could not be separated from trust in methodological choices. Informants repeatedly judged their machines to be performing well when they could adjust their processes and could understand how and why their samples were behaving a particular way. I was unsure how attractive a proposition it was to be relieved of those insights and understandings for researchers when considering using large commercial service providers.

That automation resulted in the freeing up of researchers from the details of data collection ran counter to the lived experiences of the users in my study so far. This disconnect came from an understanding that the users currently employed on projects using automation at my case study sites were bringing a wealth of experience built up from existing bench-based approaches. These users were very much interested in the details of how to make their experimental designs work on the automated platforms. PIs employed these users mainly because they had exposure to the types of systems used for liquid-handling, and their abilities to think about how they could adopt and develop these systems to facilitate established programmes of research. It seems difficult to ask these users to 'question all existing assumptions' when those same assumptions are meshed deeply with their own identities as competent researchers.

This reflection was a further flash of insight for my overall research aims and linked closely to my interest in methodological choices and identity-work (RQ2).

The next section of the chapter considers how affiliations to more low-throughput techniques might further provoke questions about boundary definitions and identity for researchers in laboratory automation and synthetic biology.

5.6 From paradigm shifts to 'mothering mode'

Perhaps because I attended the industry-academia workshop above part-way through my ethnography at the RL, and was now familiar with many of the people in the institute and their general concerns day-to-day, the slick presentations by some of the workshop talks on automation seemed counterintuitive for me. The RL PI, Kieran underlined this point when he stood up to present during the workshop and was not at all 'on-message' for the bright future that automation was currently ushering in for the biosciences. To be clear, Kieran self-identified strongly with the computer science community within the biosciences and held firm views on the need for using machine-learning and laboratory robotics to deal with the complexity of biological systems. Kieran's presentation differed from most of the others, however, in its reference to how automation vendors and commercial services were competing to share in the benefits of greater laboratory automation in the future. As I explain in Chapter 6 below, Kieran did not see himself or his laboratory as being part of the mainstream of synthetic biology and talked during interview about the lost opportunities he felt were a consequence of that marginal status. He finished his talk with a plea to those present at the workshop, that different providers of automation tools and software try to avoid what he called a 'balkanisation' of this area, particularly in the development of application programming interfaces (APIs). For Kieran, success in developing laboratory automation was a matter of perspective and position.

As a final note on what good automation means for different users in the biosciences I will now turn to my interview with Peter, the laboratory automation specialist I met at the industry-academia workshop. Peter spoke with me candidly about the risks and benefits of implementing laboratory automation systems and I felt the discussion was

useful because he was clearly not advocating a single position and recognised that automation has different meanings, values and purposes for different users. We spoke at length about 'low-throughput' robotics, an area that did not come up in any of the talks at either the EU-US, or industry-academia workshops. I wondered aloud why this was the case. Peter explained some of the tensions in this area:

> So it [a low throughput robot] won't do everything perfectly right, but you can check, you can look through the viewer and go 'oh that one bubbled' or 'that one had an air bubble' so you're still in monitoring, mothering mode but it's not as demanding of you as some of the other [high-throughput] robots. The reaction [to low-throughput robots] in the industry is very interesting. Some people said 'oh this is great. This is exactly what we need, what we're missing.' … There's another reaction which is 'oh it's pathetic. It's not very fast, it doesn't transfer things at high volume, it's not a real robot, it's like a toy'. […] [However] there is room for the low throughput [robots] … [because] you don't feel so much slaves to the robot. You're not there emptying bottles. I mean I've seen people put their white coat on, go in, pick up this… 5 litre bottle of waste and they're basically cleaning the urinal. (Peter, interview 03/08/16)

The use of the term 'mothering' to describe low-throughput laboratory users was particularly revealing. What is it about the need to monitor and intervene in sample analysis that makes it the 'mothering mode'? It seems that Peter is implicitly suggesting that low-throughput techniques are fussier and require more care. Aside from the clear gender politics in assigning qualities of care and nurture to the feminine 'mother' it is striking that Peter said some in the industry did not view this kind of work as a 'real' robot. It seems that, for some researchers, low-throughput is just playing around and is not part of the serious business of tackling large-scale high-throughput problems. Here the link between identity and methodological choices seems abundantly clear.

Finally, Peter's striking description that some operators of laboratory automation are 'merely cleaners of the urinals' was an evocative starting point for me to think about

how users of laboratories distinguish themselves from others and how these distinctions could be linked to perceptions of social status, which were being reinforced through the design of the automated systems. I explore this theme more fully by discussing engineering identity in Chapter 7 below.

5.7 Conclusion

In this chapter, I have recounted my initial observations and interactions with practitioners at two events. The aim of the chapter has been to understand how those practitioners were framing the plans and promises for automation in biology according to different organisational and disciplinary needs. Overall, I found many similarities between the promissory narratives I analysed in policy documents and the narratives about automation for the biosciences given in workshop presentations on the subject. However, it was in the debates between presentations and in conversations with individual specialists that I recognised divergent views on the importance of laboratory automation and the forms these tools would take according to different needs. It is because of these various needs that I understood the notion of a paradigm shift through laboratory automation to be problematic. I identified high-throughput approaches as attracting the most ambitious language for the power of laboratory automation for the biosciences, particularly synthetic biology. I also recognised that a high-throughput approach was far from the most common usage of laboratory automation for current researchers in biosciences laboratories. Advocates of automation were championing so-called low-throughput techniques and even proponents of high-throughput techniques were utilising low-throughput desktop robots to raise the profile of liquid-handling and encourage more researchers to engage with their processes.

Ultimately, researchers using both high- and low-throughput methodologies rely upon their existing competencies with lab-based techniques to secure their place as competent members of their knowledge communities. Indeed, I argue these competencies and sense of belonging are deeply meshed with each researcher's idea of who they are and what they can achieve; they are attentively engaged amphibious researchers. In the next chapter I look more closely at what it takes to become attentively engaged with an automated system, and explore how developing a

‘fingertip-feeling’ for both cell and robot behaviour forms part of becoming an amphibious researcher.

CHAPTER 6:

Fingers and toads: introducing amphibious researchers

'When you visit the village of the toads and you find them squatting, you must squat too. But a change in body posture, to adjust to a life among toads, does not mean you actually cross over and become a toad.' (Geurts 2003: 246)

6.1 Introduction

I begin this empirical chapter with Geurts because the quotation offers something of a provocation. To describe my time at the Rhodes Lab (RL) as a visit to the 'village of the toads' at first may sound like a derogatory statement. I hope to use this chapter to demonstrate that the opposite is true. That is, to be a toad, or for my purposes, an 'amphibian' is a hard-won and admirable achievement. More than this, the data that follow suggests that to maintain proper functioning of an automated system in the biosciences, amphibiousness needs to sit near the top of system builders' considerations. The preoccupation with the body in Geurts' work is also reminiscent of the way that informants at the RL needed to think with their bodies, to understand the movements necessary to use their hands to move liquids around in an experiment, and to think through and test these movements using robot arms and liquid handlers.

Finally, my experience observing and learning from the informants at RL involved some aspects of imitation in the form of training to use the robot platform, and demonstrating the system operations for external visitors. It was during this experience of conducting the demonstration that I began to adjust to 'life among the toads,' but as described below this crossover was always incomplete. The central thesis of this chapter is that the main operator of the system at RL had something I could not acquire in my short time learning the system: an embodied feeling of how to keep the system functioning, she could utilise her 'attentive engagement' with this platform, adjust her posture and practise amphibiousness.

6.2 Aims of the chapter

In this chapter, I aim to use extensive analysis of observations and conversations to introduce amphibious researchers. This chapter gets in to the detail of the lived experiences of laboratory automation for the biosciences. The RL team did not self-identify as part of the field of synthetic biology, as indicated in the previous chapter,

therefore I also use part of this chapter to discuss how disciplinary identity influences the way that researchers view their work, and their potential career options. Perhaps because the robot platform the RL team used was no longer tied to a particular funding stream, researchers undertook varied projects that had disparate objectives. For example, the RL team had projects covering areas including: developing advanced automation techniques; using DNA as data storage; and collaborations with text-mining colleagues to review and test previously published experimental designs. All of the RL team's work, however, utilised computer science expertise to help tackle what they viewed as the inherent complexity of biological systems. I focus on the practices of the core RL team to demonstrate that understanding biology, and the value of automation for enhancing that understanding, required significant embodied tacit knowledge by users familiar with this particular system. I view this embodied understanding as a form of essential 'fingertip-feeling' that researchers required for the successful functioning of the RL's systems.

6.3 Structure of the chapter

I organise this chapter into seven sections. The first two sections draw from ethnographic field work and I present a series of vignettes and episodes to help situate the lived experiences of laboratory users at the RL. In these first two ethnographic sections I also recount my own experiences as I completed training in how to use the robot platform. The vignette that describes my application of that training to provide a demonstration to a visiting science journalist forms the basis of a further ethnographic moment in the thesis. The next three sections describe in turn the three most salient areas of the promissory narratives listed previously. I focus specifically on ethnographic observations and interview data to show how the lived experiences of the RL researchers reconfigure promises about the timesaving, increased experimental space and enhanced reproducibility benefits of laboratory automation. In the final two sections I reflect on the remaining two promissory narratives and show that the RL's use of laboratory automation cannot be straightforwardly mapped to promises about the increased competitiveness and increased commercialisation benefits of using laboratory automation. In the concluding part of the chapter I propose a rethinking of the value of embodied tacit knowledge and argue for recognising the importance of

developing ‘fingertip-feeling’ in the successful operation of automation systems in the biosciences.

6.4 Learning to squat – an ethnographic account of training to use laboratory automation in the biosciences

I will start my account with a vignette. Around six months in to my time with the RL team I was invited to undertake training in the use of a liquid handling robot, the Bravo, which is an automated multi-well plate pipetting machine. In simple terms, the Bravo is a form of small-scale gantry robot that moves along three straight line axes, up-down, left-right, and backward-forwards, from the point of view of the user. Below the multi-channel pipette head that can move along these axes sit nine plate beds, each one the same dimensions and designed to fit a standard sized microtiter plate. The researchers at RL used 96 and 384 well plates on the Bravo. I opted to join this training session to understand the value of the Bravo to the RL team. In very basic terms I could understand that a machine capable of filling up to 384 wells at a time, rather than the one-at-a-time method used by individual researchers had timesaving, and organisational potential for conducting biosciences experiments. What I was not prepared for was the extent to which learning to use this one machine, which in itself took considerable concentration and skill, was but one small part of a hugely complex set of understandings required to use the full robot platform. In very simple terms, I was finding that timesaving and efficiency gains offered by automation for the RL team needed to be reconciled with the considerable time and effort required in training to use the system.

The platform (the Enhanced Microbiology Automation system, EMA for short) has several instruments arranged in a space which allows movement of objects (in this case microtiter plates) from one instrument, including the Bravo, to other machines, using two robotic arms. The instruments are housed in a frame which is similar in shape to a four-poster bed. The ‘mattress’ area is raised off the floor and acts as the platform upon which most of the equipment sits. Underneath the frame sit several used and unused computer hard drives, as well as the main control boxes for the two robotic

arms. These robot arms, named Tic-tac and Merlin by the researchers at RL, were by far the most difficult aspect of EMA to use. Unlike the straight line gantry system of the Bravo, the robot arms could be moved from fixed points in the system, across three dimensional-space to other fixed-points in the system, including the plate beds of the Bravo liquid handler. Learning to use the Bravo therefore required some understanding of how the robot arms had been set up to use the Bravo also. For example, the robot arm could only use one of the plate beds to collect and deposit plates when transferring between the Bravo and other equipment in the system.

The Bravo training was given by Rosalyn, a postdoctoral researcher at RL and the main user of the system who was responsible for all of the work on the platform that used the two robot arms. As I wrote down Rosalyn's instructions for using the Bravo, including how to select different wells for dispensing and different plate beds for each plate, I noticed that Rosalyn repeatedly emphasised the need to set up the Bravo so that it would work correctly with Tic-tac and Merlin. Specifically, Rosalyn was conscious of our safety because the protective light screens running around the entire system were designed to shut everything off only when the two robot arms were in operation. That is, if a hand was to break the light screens during the operation of the Bravo, it would not shut the system down, and the user could risk serious injury. This helped us trainees understand the potential power of the system.

A further consideration that Rosalyn emphasised was the need to pay attention to the small details of the setup, like pushing each plate up to the left hand corner of the plate bed, because if the plate was even marginally out of line the robot arm might not be able to grasp the plate to move it to another machine in the system. Here I witnessed that system operators needed to develop a sense of touch to feel when plates were sat correctly on the plate decks. Interestingly, operators also needed to think about the way the robot grippers would eventually grasp the plates to move each plate from the deck. This development of intuition for the correct way to set up and use plates and robot arms, as I go on to explain below, also involved developing intuition about the environmental factors that could impact the growth rates of the biological samples.

I completed the training on the Bravo along with several others, including Craig the RL computer programmer, Caitlin a PhD student with the lab, and Simon, a visiting PhD student from another part of the university. Three months after this training session, I was contacted by Kieran, the laboratory PI, and asked if I could help out the team when it went to London for a large project meeting the following month. Seeing that I had successfully navigated at least basic operations for the Bravo, the laboratory PI asked if I would mind stepping in and conducting a demonstration on the full system. The meeting in London coincided with a visit from a science journalist who was in the city where the RL was based for a short period and wanted to see the system in operation. This journalist, Bill, had an interest in robotics and artificial intelligence (AI) research and I agreed to operate the system and to be interviewed as the rest of the team was away.

I derived two important reflections from this request to act as a system demonstrator for an external visitor to the RL. First, the laboratory PI and his work were sufficiently well-known outside of the specialism to generate interest from professionals interested in the communication of science and technology for more general readership outside of Kieran's academic discipline. One of the reasons I was willing to test my basic training so early on was that I was fascinated to learn more about Bill's interest in the system and why laboratory automation and machine learning were relevant topics for his audience. I viewed this interest as the RL's version of public visibility which, for the AL team in the next chapter came mainly from their place within the core capital funding investments in the field of synthetic biology. Whilst the AL experienced pressure to meet expectations linked to their funding proposals, the RL team actively sought out opportunities to demonstrate how their research was important for future thinking around automation and the biosciences, perhaps contributing the sustaining expectations and in turn future grant successes.

The second main reflection from this episode was that my agreement to be the public face of the system was also an agreement to become part of that expectation-generating process. I felt, as Peter described in the previous chapter, that I was donning the white coat in a symbolic act that would help to cement my knowledge and expertise and give Bill confidence in my abilities to showcase the EMA system. Similar to Peter's

‘cleaners’ above, I may have been wearing the white coat but I felt my status as a system expert was rather hollow without the presence of Rosalyn and the rest of the RL team who had the in-depth understanding of the system. Connecting this to my research objectives, I could see that part of what I was engaged in by standing-in to complete the system demonstration was a form of boundary-work. I was using the impressive act of moving robot arms, liquid and plates around a system to show what automated laboratory platforms could do to enhance the biosciences. The fact that the liquid contained no biological materials and that the system only functioned once Rosalyn intervened and provided guidance, was not clear to the visiting science journalist, and would never be part of his account of the system.

To be able to run the full system demo I had spent further days being trained by Rosalyn to try to understand the correct sequences and processes required to demonstrate the system in operation. During this training I had written step-by-step instructions on a notepad as Rosalyn created the required sequence of steps on the user interface (UI). A UI is a software programme designed by the system vendors to allow users to send instructions to the automated system. To build each of the steps Rosalyn used her mouse to drag-and-drop pre-prepared steps to build larger protocols on the user interface, and moved at various intervals to press switches and turn levers. We then switched places and I successfully attempted to recreate the various stages of a full system demonstration under Rosalyn’s guidance. On the day of the team meeting in London I arrived at the now empty RL two hours early, making sure there was enough time to run the demonstration through fully at least twice before Bill arrived.

On the morning of the demonstration, the notes I had made seemed sparse and the exact sequence of events to follow seemed less than obvious. However, some of the actions, such as successful operation of the light-screen safety mechanism, were very familiar as I had watched Rosalyn complete these tasks multiple times over recent months. Some of the other instructions were clear also and I knew that it was important to first switch each individual machine on before walking around the platform and switching on the light screens, before finally turning the two individual keys that brought the two robotic arms on line. Now the system was ready and I could return to

the computer workstation and open the various software applications and load the demonstration protocols Rosalyn had left for me to use.

The protocols Rosalyn set-up were sequences of actions that the different machines needed to make to complete a certain task. For example, Rosalyn would have a set of different possible steps which might involve instructing the robot arm to: remove a plate from the Bravo plate deck; place the plate down on the central collection deck; remove the lid of the plate and place the lid on a separate deck; wait for a set period; return the lid to the plate; move the plate into the plate reader. These are just some of the steps in a protocol that uses the robot arm to move a plate that has been filled by the Bravo liquid handler into the plate reader to conduct optical density analysis. The intention during the demonstration was to show the robot arms moving a plate between each of the eight machines that made up the full EMA system. To begin the demonstration protocols, I needed to select the correct sequences of actions that Rosalyn had saved in the software program that was used to control the EMA system. I then needed to run the scripts which transmitted the lines of computer code to the robot arms and caused the arms to move in the sequence of steps that Rosalyn and other system designers and users had set up in the past.

Each time I ran the script to begin the demonstration one of the robotic arms would stop mid-movement and the system would crash, and unfamiliar errors would appear on the monitor in front of me. Rosalyn had given me some advice for tackling problems, and this advice generally involved switching the system off and then back on again in a very specific order. I checked and double-checked the programs I had open and the names of the files loaded to run the scripts; all matched the notes I had from the training with Rosalyn. With 30 minutes left before Bill was due to arrive I decided to call Rosalyn in London.

Rosalyn took the call during the meeting and excused herself from the room. I talked her through my steps and described the errors on the screen. At this point Rosalyn asked me to turn off the entire system, one machine at a time, and then close the programs and restart the workstation. Together Rosalyn and I started again and I went back to step one of the written instructions I had made during the training. We repeated

the sequences I had performed, in the same order I had tried myself that morning and the system again failed. I was reading the error codes on the screen and was about to repeat these to Rosalyn when she asked where I was standing. Rosalyn asked me to move from a seated position in front of the screen to stand close to one of the liquid dispensing machines. She instructed me to place my hand on a blue plastic cover at the top of the machine. I reached out and felt a slight wobble as I applied pressure to the cover. I felt a small 'click' as I pushed the cover. In that moment, Rosalyn had communicated her embodied knowledge of the system and, through our dialogue, helped provide instructions to ensure the system began to function again.

This experience led to three important observations for my time at RL. Firstly, Rosalyn used her body – even when operating the system from a distance – to problem-solve and keep the system operational. Secondly, I needed to move my body close to the system and use my body posture and sensation to understand Rosalyn's knowledge about the system's proper functioning. Thirdly, Rosalyn's guidance and my learning required understanding written plans and instructions and the mimicking of Rosalyn's movements. I understood those instructions most fully by listening to Rosalyn and copying her bodily movements. She was a user familiar with the system, and I recognised that that familiarity came from an attentive engagement with the RL system. Through Rosalyn's care and familiarity with EMA she could keep the system operating, almost vicariously through my descriptions of the 'feel' of the plastic cover. In tandem we shared a corporeal knowledge of the system, and by exchanging our descriptions of the way the system felt at that moment, we were able to make EMA functional again. Rosalyn was the key to this shared understanding and by experiencing her descriptions of what feels right and what feels wrong about the system, I was beginning to learn how to squat in the village of the toads.

These observations connect to the overarching argument for this thesis because my analysis demonstrates the importance of embodied tacit knowledge for developing automation systems in the biosciences. As the following sections further argue, any potential advances or leaps in understanding in biosciences research will involve some aspect of embodied tacit knowledge. When I consider this finding alongside the promissory narratives for laboratory automation and synthetic biology there are

significant gaps in understanding. This is especially apparent when considering the role of automation tools and the role of current, experienced wet lab researchers for realising the potential of those tools. In the next section I describe the RL team involvement on one project that had the specific goal of taking an existing area of research and using automation tools to simultaneously advance understanding of that research area, and demonstrate the importance of automation in that process. As the later sections show, the active engagement between amphibious researchers was essential in meeting the RL team's goals.

6.5 Project – demonstrating the potential of laboratory automation on a particular 'application domain': yeast diauxic shift

The majority of my time with researchers at RL followed their work on one project, the Advanced Automation Laboratory (AAL) project funded through a large multinational European research grant. The laboratory leader at RL, Kieran, was one of 12 named co-investigators from five different universities in the United Kingdom, France, and Belgium. Sara, the Project Co-ordinator (PC) for the AAL project, was based at a different UK university from RL and shared a long-standing working relationship with Kieran. This project was a reversal from a previous project in that Kieran, as a professor and therefore a more senior academic to Sara, a senior lecturer, had previously acted as project PI with Sara serving as a postdoctoral research associate when they collaborated on a now completed grant. For the AAL project, Kieran was listed as 'Scientific Leader' and Sara as 'Project Co-ordinator'.

The naming of these roles seemed similar to my experiences on research projects where the overall direction of the study was the responsibility of a Principal Investigator (PI), and the PI would sometimes hire a project manager to help manage the delivery of the project goals. A major difference for the AAL project, which had implications during some project meetings, was that Sara was the overall lead for the project and Sara's institution managed the main part of the grant, while Kieran's institution was named as a collaborator. The fact that Kieran and Sara were close personally and experienced long-term working relationships also meant that project

meetings could be heated at times, as they held frank exchanges of views about the best ways to progress the project and plan the experimental work. These tensions extended to different project team members with computer science or biological sciences backgrounds. As Rosalyn (a postdoctoral researcher) described to me at one point, sometimes the difficulty in working between computer scientists and biologists is if the computer scientists do not have vast amounts of laboratory experience:

> Well if you've not actually done it in a lab you're going to have different kind of ideas and sometimes people do come up with stuff from different angles. Sometimes it's good; sometimes it's frustrating because they go "what about this thing?" When it's not actually a thing that's that relevant but they can get quite obsessed on specific points. (Rosalyn, interview 11/07/2016)

Although the main project co-ordinator was located elsewhere in the UK, the RL was responsible for the bulk of the experimental work because it was home to an established laboratory automation platform. With Kieran as Site Project Lead and Scientific Leader, the RL team also included Craig, a computer scientist and programmer, and Rosalyn, who had completed an MSc. in bioinformatics and a PhD in cell biology. I also had conversations with a technician named Anya and two PhD students, Caitlin and Yan who were not employed directly on the AAL project although each laboratory member would share equipment and laboratory space with Rosalyn so sometimes my observations, even on this specific AAL project, involved the wider team.

As detailed in Chapter 1, my primary interest was in the lived experiences of laboratory users, particularly users with significant interest and engagement with laboratory robots. For this reason, I spent many hours with Rosalyn as she was responsible for executing experiments using the robot platform. Other project partners advised on and planned various aspects of the experimental design, and the development of databases and models. However, during the period of my observations only Rosalyn carried out experiments using the robot platform. Moreover, I did not observe Rosalyn contacting other project members for assistance with the day-to-day problem solving required to keep the robot platform functioning. Rosalyn did require assistance and advice at

various stages of the project work, contacting instrument vendors, and speaking with previous users of the system to deal with system failures; this theme is explored further in section 6.7.1 below. Rosalyn's use of the robot platform was one part of the AAL project and I now explore the background to this project to understand why this group of researchers chose yeast diauxic shift as its application domain.

The objectives for the AAL project focused on using a combination of bioinformatics, database construction, machine-learning and laboratory automation to improve current understanding of diauxic shift in yeast. The term diauxic means double growth and diauxic shift for the AAL team referred to how yeast cultures first use up the available nutrients that the researchers have placed into the plate or well containing each yeast strain. This nutrient is an energy source that kicks off a period of fast growth as the yeast cells multiply and turn the energy source into ethanol. Once the readily available nutrients are used up, or metabolised by the yeast cells, the growth rate slows down because the cells require more energy to continue growing. However, after the initial growth period has slowed down or stopped and no more new yeast cells are forming, a second period of growth begins as the cells reorganise and start to utilise the initial ethanol they produced as a new energy source.

Diauxic shift is important for biomedical applications because it is used in biology as a model for understanding general cellular reorganisation. In cancer treatments for example, understanding the metabolic shift to lactic acid from glucose in solid tumours (known as the Warburg effect, in which lactic acid is understood by scientists as the equivalent in animals of ethanol) is believed to help explain tumour growth (Gatenby and Gawlinski 2003). For researchers concerned with cellular reorganisation in the ageing process the shift from lactic acid to glucose has been shown to relate to a cell's stress response and is linked to greater cell lifespan (Kenyon 2010).

The project team, mainly a combination of computer scientists and programmers, and a smaller number of biologists, aimed to increase the knowledge base on yeast diauxic shift. In the process they hoped to create probabilistic databases containing high levels of facts and rules and to use a combination of scientists, robots, and machine-learning to enable faster predictive modelling for yeast cell biology- quicker, that is, than would

be possible by scientists working without these instruments. As noted above, yeast diauxic shift is an established research area and the main benefit offered in the proposal for this team's study was that their robots and specialist software programs could improve understanding by creating detailed records of the separate steps that contribute to cellular reorganisation in yeast.

The previous section described the reasons why researchers at RL chose to focus on yeast diauxic shift as an application domain for laboratory automation. In the sections that follow I turn to the five promissory narratives surrounding laboratory automation identified by analysing policy documents and attending various events during the research, as outlined in Chapter 4 and 5. To re-cap these are:

- (Narrative 1) Automation will result in more **time** for researchers (because robots are more efficient and more accurate, especially on repetitive tasks).
- (Narrative 2) Automation will enable greater **experimental space** (i.e. increased parameters and the ability to tackle problems with very large numbers of variables).
- (Narrative 3) Automation will enhance the **reproducibility of experimental results** (by breaking down experiments in to recordable steps and standardised protocols).
- (Narrative 4) Automation will increase **technological capacity** (making laboratories more competitive in international funding arena).
- (Narrative 5) Automation will provide further **opportunities for commercialisation of products and services** (either directly by using automation to build DNA, or indirectly by creating research economies based on consumables and service plans).

To explore the ways in which laboratory users' lived experiences supported or challenged these narratives at the RL, I concentrated my efforts on observational work and follow-up interviews, primarily spending time with Rosalyn as she planned,

adapted and carried out the yeast experiments for the AAL project. To understand Rosalyn's experiences in relation to the five promissory narratives, the organisation of the working environment and the specific set up of the laboratory space and robot platform require some explanation.

6.6 The RL space and connections to other institute systems

The office where Rosalyn, Craig and I had desks was at one side of a large central atrium space. To reach the laboratories used by Rosalyn, we first walked across a bridge that connects the RL offices, and a series of other similar open plan and enclosed office spaces, to the corridor-style desk arrangements used mainly for postgraduate working spaces. At intervals a number of double doors along this corridor led through to the bench areas used by the different laboratories located in the institute. For access to the robot platform we walked through one large space occupied by a number of unfamiliar researchers from other laboratories, before entering through another double door and into the room dedicated to the work of Kieran's team using the robot platform.

Most of the building seemed to be fitted with motion sensing lights, which illuminated as people entered a space that had not been in use for a set period. Perhaps because Rosalyn was the only person to use the dedicated robot room regularly, and needed to move to other spaces as part of her work, I only observed the light motion sensing in two places in the institute, in the bathrooms and when entering the robot room. Each time I entered the robot room in darkness I was reminded that only very few people within the institute where the RL was based had a routine need for a robot platform. Moreover, it was clear that a very small number of users, even accounting for the multiple projects, had operated the robot platform and platform iterations utilised over a ten-year period.

My findings suggest that the specific knowledge and skills required to successfully operate the RL robot platform have been practised by a handful of skilled researchers. Each user of the system maintained the knowledge-base and contributed their own particular pieces to the framework that allows the machines to continue to work for their current needs. In terms of bench based 'wet' laboratory work the robot room

housed one containment hood which Rosalyn used to prepare mixtures and load plates ready for use on the automated platform. For the most part, whenever significant wet lab bench-based work needed to be completed we would leave the robot room and ascend one flight of stairs to a shared laboratory space above.

In this space there were numerous fridges, freezers, centrifuges, adjustable pipettes, polymerase chain reaction (PCR) machines, consumables and printed protocols, and a bioanalyser used for DNA sequencing, as well as autoclave tape, waste receptacles, pipette tips, tinfoil, pens, rulers and many other items which were needed by the various groups of researchers using the benches on a daily basis. It made sense for Rosalyn to conduct most sample preparation in this fully-equipped laboratory space before taking specific items down to the robot room and completing the parts of the work that used the robotic platform. One of the implications of this need for a fully-equipped, bench-based laboratory alongside the robot platform was that the robots could not meet all of Rosalyn's needs on a daily work basis.

A further working space I visited regularly with Rosalyn was the stores department in the basement. As a large research-active institute the building operated a centralised system for ordering and collecting items needed in day-to-day work. There were hundreds of researchers working in different labs and utilising a huge number of products that needed to be ordered in from external suppliers. In addition to the continually stocked items such as oxygen which many laboratories required regularly, individual orders placed through specific labs would also be collected from stores as they became available. One of the highlights of a visit to stores was queueing up to check a printed list pinned on a notice board, listing items received and ready for collection.

Rosalyn talked me through the stock ordering process and showed me the differently coloured order booklets – one for VAT, one for non-VAT items – used for ordering products, and the coding system for allocating the costs of these products to the correct laboratory and project budget. The system was paper-based with carbon paper used to create duplicate copies of each order. A number of the slips were sent to internal administrators and a copy was retained in Rosalyn's order book as a record of orders

placed to date. I found it striking that Rosalyn relied upon a paper-based system for the ordering of essential stock and consumables for the robot platform.

Participating in the coloured booklet system was not optional because of the way that this part of the university currently managed procurement. There were many hundreds of researchers in the building working across dozens of projects and clearly the coloured booklet system was well-established and worked adequately for managing the ordering of goods and allocation of costs to projects. I reflected on the use of the paper ordering system during subsequent writing and recognised that many processes that keep universities functioning still require an element of paperwork; the requirement for ink signatures on some expenses claims is one such process. There might be many potential benefits in switching to a paperless expenses system with all claims submitted electronically, however making this change would require significant reorganisation of various systems and investment in new training and IT resources for both claimants and the finance teams responsible for processing claims. If the system is working adequately in paper form, therefore, the justification for large scale systems overhauls would need to be substantial.

This reliance on paper did raise further questions about exactly how far an automation platform could increase the efficiency of researchers' time in the laboratory. No matter how efficient any system is, if that system is closely linked with another system – university procurement processes for example – then potential efficiency gains one system offers must also be seen in the context of the inefficiencies of the interconnecting systems they operate alongside. For example, rapid experimentation and analysis enabled by automation might be affected by the supply of relevant consumables needed for the platform to function (these issues of productivity and efficiency are explored further in section 6.7 below). Furthermore, it is important to recognise that when commentators label a system as 'inefficient' the justifications for that judgement will come from comparisons to other methods for completing those same tasks (e.g. expenses claimants advocating an e-submission system that does not require expense forms to be printed, signed, and posted to finance officers to process for payment). However, implementing a new e-system would use resources and would require training for all university staff, potentially risking errors and delays in making

payments. Systems designers must weigh the long term proposed benefits of the system against the short-term challenges major changes would create. This is a clear example of a debate about future value helping to legitimate actions in the present (Brown and Michael 2003, Frow and Calvert 2013b).

For Rosalyn and the RL team the paper procurement process worked adequately well for their needs. Although Rosalyn did spend a great deal of time considering the cost implications of her experimental choices she was understandably less familiar with the exact administrative set up and how the different project partners took decisions about acceptable spending and approval processes. With the PI and Project Co-ordinator located at a different institute I wondered if the differing systems used at each institute affected the ability of the team to have a real-time fix on the project budget, and if and how Rosalyn was able to take decisions on spending. I learned from the funding proposal that €72,000 had been requested for consumables and maintenance of the robot platform over three years. I also later discussed with Rosalyn the need to speak to Kieran before arranging payment for essential system repairs. These issues around system maintenance and consumables were to become more salient as I explored with Rosalyn the constraints she faced working with a robot platform and instruments that were now a few years old (see section 6.11 below for more details on the theme of research economies in laboratory automation).

The four main locations Rosalyn used on a daily basis were: an open plan office shared with Craig, a number of PhD students associated with the lab, and me; the robot room containing instruments arranged around two robot arms; a wet lab bench space shared with other laboratory groups, one floor up from the robot room; and the stores area in the basement (the liquid nitrogen freezing facility was also in the basement and was visited when samples were being retrieved from, or placed in to, long term deep freeze). The team also made use of a shared kitchen down the corridor from the office space and the institute cafeteria located on the ground floor. I spent my time shadowing Rosalyn as she moved around the various work spaces, writing brief notes on a pad, and typing up observations and reflections when we returned to the office.

I now turn to the five prominent narratives detailed above and consider how the lived experiences of the RL team matched up with those promises for laboratory automation. As I have just outlined, automaton advocates often propose that certain inefficiencies in a system can be improved through increasing automation. At the same time, the proffered future benefits for introducing a new system must be considered in the context of the way existing practices are organised. The following section unpacks these themes further by discussing the promise that automation will result in timesavings for practising bioscience researchers.

6.7 Automation will result in more time for researchers (Narrative 1)

As I explained in Chapter 4, one of the promissory narratives surrounding laboratory automation and synthetic biology is that robots complete certain tasks with more efficiency and accuracy than is possible by researchers working without such systems. My aim therefore was to understand if and how automation and robotics increase productivity for laboratory users, and whether the lived experience of using such systems was an increase in the amount of time available to researchers for daily tasks. To do this at the RL I needed to find out how Rosalyn and the team organised their days, what they needed to do to complete essential tasks, and how using the laboratory automation robot platform for an established application domain – yeast diauxic shift – affected the time spent on different elements of daily work plans.

The separate working areas described above meant that Rosalyn and I spent significant periods walking between the offices and the robot room, and up and down stairs to reach the wet lab on the floor above or travelling in the lift to collect packages from stores in the basement. The different locations were utilised for the availability of different instruments and consumables. For example, to begin a polymerase chain reaction (PCR) we would always head up to the wet lab where the PCR machines were set up on benches. For any DNA sequencing requirements, we would walk from the wet lab bench around to a side room that contained an Agilent Bioanalyzer, which researchers used to perform gel electrophoresis.

If samples were needed from the long-term deep freeze we would head down to the liquid nitrogen room in the basement, put on our safety goggles and large protective gloves and retrieve them from the canisters. Similarly, if Rosalyn had ordered a new batch of microtiter plates we would get the lift down to the basement, visit stores and check the printed list to see if the package was ready for collection. As a result, during my initial observations I struggled to see exactly how the automated platform could have a significant impact on the efficiency and productivity of Rosalyn's daily work routine because a significant amount of her time involved navigating physical spaces and university structures to get experiments up and running. Moreover, I also witnessed a number of examples in which using the automated platform introduced additional delays to the work routine.

After further reflection I could see that to understand the timesaving capacities of the robot platform I needed to view the platform not as a system separate from the existing routines of the majority of other researchers not using automation significantly in the institute. Rather, for the RL to generate trust and confidence in the results of the experiments conducted using the liquid-handlers, the RL team needed to embed the system into the existing structures and systems of the university. For example, all of the data produced by measuring growth rates in the plate reader of the EMA system was stored on local hard drives. The RL team did not link the EMA system to the university's IT network. Therefore, each time the RL team needed to share data with each other and their project partners they needed to download files on to portable USB drives and carry the drives back to their own PCs in the main office. The motivations for keeping the EMA system separate from the main university network seemed twofold: first, the entire system had been transported from another institution and installed at the RL when Kieran changed jobs and got agreement for the university to purchase the hardware from his previous employer. The system was therefore not purchased through the usual university IT procurement process and it was left to the RL team to liaise with the original system designers to successfully install the hardware.

Secondly, because of this history of transporting an existing system across the country and the difficulties in setting it up for Kieran's new lab, Craig and many of his

predecessors were constantly worried about making changes to the system that could not easily be rectified. In fact, Craig explained to me that all the hard drives continued to use the Microsoft XP operating system (OS) and that any possible benefits from upgrading to a new Window OS were far outweighed by the risks involved in causing major systems failures that could be impossible or very costly to repair. In terms of timesaving and efficiency potential for the EMA system then, it was not clear cut that large-scale high-throughput experimental capacity was the main consideration in this area. Craig, Rosalyn and the rest of the team had to also work with the legacy operating systems that the EMA system relied upon, even if those systems became slow-running and sub-optimal over time. The key for all the system users was keeping the system functional. Thinking again about the expenses claim example above, it seems clear that for automation systems too there are discussions about potential improvements that could be made to the system but that those improvements in the long term must be weighed against potentially large-scale disruptions in the short term. In the end, keeping the system operational is paramount.

Another consideration for keeping EMA operational was the need for consumables. To keep the supply of consumables regular the RL team needed to organise their procurement through the internal university stores. Working with and visiting stores involved navigating the university structures and processes, including the stock ordering system outlined above. Understanding the best way to navigate this lift system and knowing good and bad times to visit stores is important for users who wish to use their time efficiently which was especially relevant for Rosalyn as she received orders for different consumables required for operating the robot platform. All consumables arrive through stores and often the fastest way to check if an item had been delivered was to take the lift down and check the printed list pinned on the wall next to the stores service counter.

By interacting with colleagues in stores and getting to know the routines of the procurement process in the university, Rosalyn and the RL team could ensure they had all necessary samples and consumables onsite to plan their weekly workload. Occasionally however, having the right types of consumables in store could severely affect the timescales for completing experiments. For example, Rosalyn discussed

consumables with her team a number of times, especially the types of plates the group should use for different experiments. These discussions often began when sample analysis results appeared inconsistent or the sample had not grown as expected. As well as considering environmental factors that could influence growth rates, including room temperature and moisture levels, by using automation platforms Rosalyn and the team also had to consider additional possible factors that their use of such platforms may introduce to the experiment. Choosing a plate type was one of those consdierations.

Rosalyn and the team also had to negotiate the building architecture to meet the seemingly simple goal of restocking consumables. In a quirk of the building design it was possible to reach every floor of the institute using either a staircase or a lift, but to access the stores area in the basement researchers had to use one of a number of industrial style lifts; there was only one accessible staircase to the basement located towards the other side of the building. Stores were only open twice each day (Monday to Friday), and for one hour each time. One effect of this arrangement was that the lifts were always congested with people travelling down to stores or back up to their work space, often carrying items that were fragile or hazardous.

If researchers wished to transport liquid nitrogen for example, health and safety policies meant that people could not travel in the lift at the same time as the liquid nitrogen canisters. When collecting such a canister the researcher would be responsible for erecting a ‘do not enter’ warning barrier in the lift before selecting the required floor and leaving the lift; the researcher would then rush to meet the canister on the correct floor using a different lift. Any person calling for the lift on an intervening floor would be met with the barrier and would know not to enter and to wait for an alternative lift. Although I had completed a laboratory safety training session as part of my induction to the RL, learning the rules of the correct lift safety process involved my observations of others’ actions. I followed the lead of more experienced stores visitors and was able to assist Rosalyn when transporting samples from the liquid nitrogen areas in the basement.

For the RL then, part of the successful functioning of the EMA system involved replicating the actions of other researchers not connected in any way to the automated platform. For all researchers in the building, automation advocates or otherwise, successful functioning in their experimental systems involved successful mimicking of the actions of other experts who seemed knowledgeable and trustworthy. As I go on to argue below, these same principles applied to the successful replication of human action by a machine and laboratory users relied on their own and others' embodied tacit knowledge to judge successful mimicking (RQ3).

Often, for Rosalyn and the rest of the RL team it was not a straightforward question of taking an existing process and using the robot platform to complete that process more quickly. Building trust and confidence in the successful functioning of the system was the main priority and often the team would prefer to spend longer on building that confidence and explore ways to improve trust in their results and their equipment. Most of the time the RL team was not repeating one experimental process it had perfected, trying to make that process more efficient; rather, the team was moving across problem spaces and trying out new approaches that required movement between tube-based bench work and microtiter plates on the automated platform. For these reasons, a major consideration when thinking about the timesaving capacities of automation is the need to troubleshoot perceived problems either in the results or the platform set up. I now turn to the theme of automation and troubleshooting.

6.7.1 Automation and troubleshooting

When Rosalyn and the team used the robot platform one of the issues they faced was that cell samples would not mix effectively and would clump at the bottom of the plate wells. This clumping affected the accurate measurement of growth rates, a vital aspect of the diauxic shift experimental design. Rosalyn would know quite quickly if the cells had not mixed with the growth medium in the plate wells whenever a plate was inserted into the plate reader. If the number of cells counted in a specific well were much lower or higher than the rest of the wells on the plate then this was a sign something had not worked as expected. To confirm her suspicions Rosalyn would first remove the plate from the reader and then hold it up above her eyeline and check to see if certain wells looked cloudy or had visible clumps not seen in other wells. This

clumping would suggest the liquid-handling robot had not mixed those wells effectively enough to ensure an even optical density reading. This problem of clumping was the first of several problems that Rosalyn and the RL team encountered when using the robot platform.

Each of these problems, as I demonstrate below, had the same pattern: Rosalyn would use optical density readings to determine growth rates were in the correct range; if the growth seemed unusually high or low she would inspect the plate visually for further signs of difference between each plate well. If the growth rates continued to be outside expectations Rosalyn would cycle through a range of possible causes. In the majority of cases the source of the problem appeared to be either (a) an environmental factor such as room temperature or moisture level, or (b) a mechanical factor such as the robot arms or liquid handlers introducing unwanted variables to the experiment. To build confidence in the platform and her results Rosalyn inspected samples visually, she inspected the pipette tips of the liquid-handling robots, and she used fingers and thumbs to manually pipette mixtures on to plates before returning the plate to the robot platform to conduct analysis in the plate reader using the two robotic arms. In short, Rosalyn used her embodied tacit knowledge to generate trust in her results. Moreover, Rosalyn used that same embodied tacit knowledge to teach other system users how to have intuition about the system and to keep it functioning. As described above, I was one of those users.

A further example of Rosalyn using her embodied tacit knowledge is her solution for the mixing and clumping problem identified above. She created a programme for the liquid handling robot that would mirror the method that Rosalyn herself would use to mix different agents manually, using a single channel pipette. To help mix different agents with a pipette at the bench Rosalyn would first add in the correct amounts of all the agents to each sample, taking care not to contaminate different samples or agents by using disposable pipette tips. Once she had added all the required elements Rosalyn would then draw up and express the contents of each well several times, by moving all the cells and agents back and forth between the pipette barrel and plate well the mixture would become evenly mixed. To mirror this process using a liquid-handling robot was not straightforward. The velocity of liquid dispensing needed to be finely tuned so that

cells were not flushed out by the force of each aspiration. Equally, if the liquid-handling robot pipette tips retained even a small amount of the liquid from the well after each aspiration this would also affect the optical density readings later on. The robot platform did have a feature which allowed Rosalyn to programme a gentle shimmy of the plate from side to side before removing the pipette tips after aspiration. This shimmy mimicked the way that Rosalyn would gently shake and tap a single channel pipette tip against the side of a well when pipetting manually.

A further complication was that the angle at which the pipette tip entered the well could also disturb the cell culture and affect the plate readings if not controlled. Again, the manual method Rosalyn used was to place the tip at an angle and aim for the corner of the well bottom, avoiding the centre. The robot liquid handler was set up by previous users to aim the pipette tip directly into the centre of each well. Before Rosalyn adapted the programme to aim off-centre the liquid handler had been known to remove the entire cell sample when the robot was used to extract and express the liquids, which Rosalyn thought contributed to the clumping issue. Here the dexterity of Rosalyn's wrists allowed her to adjust the angle of the pipette tip each time she drew up and aspirated the liquid. She could tweak the angle of the tip and the speed of the mixing for each individual well if required, and she could target wells that seemed to have obvious clumping to ensure these wells were drawn up and aspirated additional times. This kind of flexibility and individual targeting of different wells was extremely difficult using the liquid handling robots because each pipette tip is programmed to enter and exit the plate wells in the same way. This kind of standardisation is what automation advocates say will enable researchers to practise experimental work efficiently. For Rosalyn and the RL team these kinds of rigid standard approaches were challenges to overcome, especially when these researchers needed to develop more confidence in their results.

The clumping issue returned at different stages over the course of my time at the RL. In addition to creating new program scripts and building extra steps into the yeast experiments, to address the clumping issues, Rosalyn also reviewed the type of plate she was using with the liquid-handler. There are many different manufacturers of 96 and 384 microtiter plates. Despite each plate needing very similar designs and

dimensions to be compatible with the liquid-handlers at RL, different brands did not work consistently with the system. For example, Rosalyn had needed to switch plate manufacturer when one promotional (and therefore free) supply of plates came to an end, which instantly caused some of the system protocols to crash mid-sequence, having been operating successfully prior to the change in plate manufacturer. However, because of the clumping issue Rosalyn decided a switch to a different plate was worth the risk, so went ahead and ordered in plates from a manufacturer that specifically focused on the design of the plate well bottom to help reduce clumping. Again, in terms of the efficiency and time saving capacities of the RL platform these trials with different consumable manufacturers introduced new challenges that Rosalyn and the team had to manage to keep the system functioning. Even apparently standardised plate sizes did not guarantee system functionality, and the operation of the EMA platform was notably fragile and sensitive to even minor changes in the set-up.

6.7.2 Robots can extend the potential duration of experiments

Sometimes Rosalyn and the team managed the fragility of the system sufficiently to allow the platform to complete sample analysis for sustained periods of time. In theory the EMA system could complete sample analysis overnight or at weekends using only the plate reader (i.e. no robot arm), but this did not allow continued incubation between each of the optical density measurements. After trying several experiments there was a theory that growth rate was low because not enough air was getting to samples. Rosalyn introduced a ‘lid lift’ protocol between the plate reads, in which the samples would be brought out of the incubator and the lid lifted off by one of the robot arms. This would then allow air in to the samples for a set period before the lid was replaced and the sample transferred to the plate reader, ready to be placed back in the incubator.

The amount of data collected via this method was considerable when successful, running for forty two consecutive hours, taking readings every twenty minutes. This is strong evidence that robots do increase the potential for continuous working on repetitive tasks for specific experiments without the need for a person present to monitor the system (although, as addressed above, the likelihood of stoppages and delays are increased when people are not present). One of the keys to this potential is

that what needs to be completed is repetitive. In this case Rosalyn programmed the robot arm to: remove the plate from the incubator; place the plate down on the available deck; remove the lid of the plate and place the lid on a separate deck; wait for a set period; return the lid to the plate; move the plate into the plate reader; remove the plate after the reading step is complete; place the plate back into the incubator. This process was repeated every twenty minutes for up to forty two hours, usually consisting of evenings and weekends as this allowed Rosalyn to use and adapt the system during normal working hours. In this example, the RL team could utilise the analysis capabilities of the robot platform during hours the team would not be present in the laboratory. In doing so, potentially the EMA system provided efficiency gains for the team and freed up the platform for more varied uses during normal working hours. However, the lived experience for Rosalyn and the team was that failure rates and the need to conduct non-repetitive tasks often curtailed many of the potential efficiencies in out-of-hours analysis work.

This finding is one of the clearest challenges to the promissory narrative that automation will save researchers time in the laboratory: my evidence suggests that the capacity for such timesaving by using robot platforms is reliant upon the existence of significant repetitive work for laboratory users. Moreover, the failure rates during even highly repetitive tasks remain significant and using robot platforms might introduce as many additional challenges as it solves for academic researchers in the biosciences.

6.8 Automation will increase experimental space (Narrative 2)

The previous section described how the use of robot arms extends the length of time over which an experiment can be set to run by laboratory users, resulting in large amounts of data for analysis. The RL proposal for the AAL project stated that machine-learning algorithms would be used to help manage and make sense of that data more quickly than would be possible when not using machine-learning. In relation to the yeast diauxic shift experiments Rosalyn (interview 11/07/2016) explained how the robot platform uses machine-learning algorithms, which she describes as a modest form of artificial intelligence (AI), for diauxic shift pattern recognition: '…basically [the robot platform's] AI is "does this curve match the good curves?" "Does this curve match the bad curves" and how to classify curves.'

Craig was involved in taking the data produced during the optical density plate readings and using these pattern recognition programs to create growth curves for each of the samples. After completing a full successful run of the system (forty two hours) Rosalyn downloaded the data from the robot platform room onto a USB pen drive and took it back to Craig in the offices. Over the course of a few hours Craig worked with the data and produced graphs. Rosalyn and Craig communicated via email and spoke across the desk, with Craig getting up and walking round to look at Rosalyn's screen at one point to view the graphs together. Rosalyn was sure diauxic shift was not occurring because the modified strains were behaving differently from the wild type control, although each of the modified strains looked similar to the others in terms of growth rate. The use of the AI programme could help to identify patterns and anomalies between growth curves however the decisions over what counted as a 'good' or 'bad' curve were taken by Rosalyn and Craig.

Rosalyn liaised with collaborators before deciding how to move forward with the experiments and how to encourage diauxic shift in the modified yeast strains. Similarly, to the clumping issue outlined previously Rosalyn had a number of working theories as to why the yeast may not be growing as expected. The most likely issue was that the samples were not getting enough oxygen to allow for the two-stage growth that Rosalyn and the AAL collaborators were expecting. As described in the automation and troubleshooting section above one way that Rosalyn decided to get more oxygen to the samples was to add an additional step to the robot platform sequence that moved plates from the incubator to the plate reader every twenty minutes.

In Rosalyn's lived experience of automating the yeast diauxic shift experiments, the robot was excellent for running complicated sets of sample preparations with minor differences between each variable. The power of the software interface and liquid-handling robots came from Rosalyn's ability to think about the whole set of samples and variables and to plan the changes needed to test several variables simultaneously. This capacity for planning and execution was something Rosalyn (Interview 11/07/2016) talked enthusiastically about when I asked about the value of automation for her work, and she was clear that some of that complex execution would not be

possible without the use of a robot platform: ‘You can cherry pick which wells it’s going into; you can set up stuff that would be far too complex … there’s no way we [humans] can do that kind of precision and accuracy.’

However, what the robot platform could not do was to complete those complex experimental designs smoothly without failure or intervention of some kind. The impact of changes to the consumables used or from any adaptations to the steps of the process required to improve growth rates meant that Rosalyn’s thinking through of conceptual possibilities related to the yeast work also involved thinking through the potential problems and solutions for failures in the automated system. Her theories about yeast behaviour had to be joined up with theories about why the machine was behaving a certain way. As Rosalyn stopped and started the robot arms, tested various positons and speeds, and considered the many potential factors that may be influencing the success or failure of a particular task, she was applying sophisticated problem-solving skills in both her yeast work and in her robot work. I argue that the potential for an expansion of experimental space offered by the systems at RL must be viewed as relative to the skills of Rosalyn as an amphibious researcher. Viewed in the context of the promissory narrative that automation will enable greater experimental space in the biosciences, my findings show that expanding experimental space cannot be viewed as an intrinsic capacity of the instruments in isolation from a skilful operator. That is, my data refutes the implicit technological determinism that automation will radically alter the future of the biosciences because my data shows how skilful operators are needed for any automation system to be judged successful.

6.8.1 Embodied knowledge and making leaps among knowledge communities

One way to think about experimental space and automation is to imagine the expansion of experimental space as an extension of the epistemic infrastructure available for practising researchers. Rosalyn was aware of the rhetoric around artificial intelligence (AI) and, as noted above, recognised the limitations of the AI systems for completing some of the complex tasks of experimental design and application. Rosalyn seemed to divide the potential of EMA into two areas when considering the system as a tool for extending her epistemic infrastructure. Firstly, the designing, planning, and adjusting of experiments can be aided by robots and automation but the synthesising of results

and making connections over time and space was something Rosalyn still felt was completed by practising scientists: '…so I don't think it [automation] cuts out that sort of thing [making novel connections in data]. It just makes how you get [to] the kind of original leaping-off point a bit more systematically.' (Rosalyn, Interview 11/07/2016)

Secondly, Rosalyn still very much relied upon collaborators on the project team to help her work through problems with her results. The introduction of automation does not replace the need for her to be engaged with her community of peers, and for this community to have a well-developed understanding of the how the cells and samples they work with behave under different conditions:

> With the yeast trying to get diauxic shift to show the different metabolic phases. It turned out that one of the things that was stopping it working properly was the pH, which was a consequence of how much sugar we put in at the start because if you break down more sugar into ethanol you get more carbon dioxide and the pH drops way lower but that's a thing you'd have encountered anyway if you were doing it just on a small scale so it's less about that sort of thing [automation] and more about kind of just knowing how to handle things. (Rosalyn, Interview 11/07/2016)

This ability to know how to handle things applies equally to the robot platforms as to the biological substrates the RL collaborators worked with. I witnessed time and time again the specific intelligibility that Rosalyn and her team brought to using EMA, how she was able to understand the movements of the robot arms and the machines they served, and how Rosalyn moved between her own physical aptitude for pipetting, the computer systems she was developing, and the advice and guidance from collaborators to replicate those movements. One theme Rosalyn returned to on several occasions was the simple benefit that automation can have for reducing the repetitive strain injuries she had sustained at a previous job, when her job involved the continual repetition of similar pipetting movements. This benefit of automation, to help do away with the 'wrist destroying work' (Rosalyn, Interview 11/07/2016) of manual pipetting was a valid reason for using robots to complete very repetitive work. Recognising that

the wrist is an essential component of the pipetting process, and is used so heavily as to become damaged, also helped me to understand that when Rosalyn talked about making leaps in her experimental work, it is important to recognise that her body is part of that leaping. Rosalyn and the other amphibious researchers she worked with had important embodied tacit knowledge, a fingertip-feeling for increasing knowledge of biology.

This is one area where my observations of Rosalyn working with the robot platform, and subsequent descriptions of that work in interview by Rosalyn seemed to be somewhat disconnected:

> I think it's more about the ability to design experiments and so forth and make leaps, it's less about doing the actual wrist destroying work. If you can automate that in a way that is more efficient [than] for humans then I think that's fine it's just kind of making sure you still are intelligently designing what you're doing. It's more about the cycle of data analysis and kind of what that actually means in terms of your hypothesis is where the actual kind of PhD level stuff comes in because anyone can pipette a bunch of stuff [laughs]. (Rosalyn, interview 11/07/2016)

The disconnect I felt was in Rosalyn's minimising of her skill in combining intelligent experimental design with an intuitive embodied process for gaining trust in her experimental results. The many examples of embodied tacit knowledge I observed and describe above seem invisible to Rosalyn as she talks about what it is that she sees as valuable in the furthering of biological understanding. I argue that Rosalyn does her body a disservice by not recognising the dexterity and knowledge she has for handling both the robots and the samples in her daily work. Perhaps more importantly, by observing the practices of the RL team, I have shown that lived experiences and promissory narratives are not stable entities that can be relied upon as predictions of future value for automation in the biosciences. Observations of practices, on the other hand, offer clear evidence of the importance of skilled operators and embodied knowledge for a successfully functioning automation system in the biosciences.

6.9 Automation will result in more reproducible experiments (Narrative 3)

My observations and experiences suggest that Rosalyn does not give herself credit for the achievements she makes every day using the robot platform to 'pipette a bunch of stuff'. One area where this observation seems valid is when automation is positioned as a way to increase how reproducible an experiment is. A major aim of the AAL project was for the EMA platform to provide a 'superhuman ability to record experimental actions and results' (AAL proposal document). The experience of spending time with the RL team convinced me that many of the experimental actions they performed were exceptional precisely because of a human ability to connect bodily movements with the movements and behaviours of the machines and cells they worked with. They could carry these understandings with them as the RL team debated with collaborators over video conference, or colleagues over the desk. These were the very-human capabilities necessary to have confidence in the experimental actions the group were taking, and to have trust in the experimental results that they generated from those actions.

6.9.1 Mitigating for 'edge-effects'

One way that Rosalyn built confidence in her results was to plan her experiments in a way that offered comparisons between identical sample mixtures, placed in different wells on the same plate. Rosalyn suspected that some of the experimental results were being influenced by 'edge-effects' (Rosalyn, interview 11/07/2016). That is, depending on where a sample was placed on the microtiter plate, Rosalyn believed that the optical density readings taken to plot the growth of each sample were being affected by too much oxygen getting to the outside rows of the multi-well plate. An alternative edge-effect Rosalyn described was that the outer rows of samples may have suffered from marginally more evaporation that the inner wells on the plate, again the effect being that the growth rates of the inner and outer wells plotted differently on the growth curves after optical density readings. By comparing samples from the middle and edge Rosalyn wanted to make sure that this was not occurring. In addition, each well around the entire perimeter of the plate was filled with growth medium only, and to the same volume as the samples in the inner wells. The idea behind adding growth

medium around the plate edges was to help protect samples from the edge effects of evaporation.

I asked Rosalyn (interview 11/07/2016) about using the robot platform to mitigate for these edge effects and she said, “I sometimes specify it”. Therefore, it is possible to use robotics and automation to put in these checks for edge effects but Rosalyn did not think it was necessary in every case. It is only when the results appear unreliable, after measuring optical density that Rosalyn decided to make adjustments for edge effects. There is more flexibility in choosing to check for edge effects when pipetting manually. Although it is not as straightforward to build this in to the automation protocols, it is possible to do so. Perhaps because it was easier this way, Rosalyn opted for the manual method over designing automated scripts that would complete the above process more quickly. However, a more important reflection from this episode for my purposes is that Rosalyn’s motivation for using edge-effect mitigation in some cases and not others was the belief that some samples were not behaving as expected: she did not trust the results. By having multiple copies of the same sample on different parts of the plates Rosalyn could continue to run the experiment, mitigate for edge-effects and select the well that appears to have grown according to the expectations that she, and her team of collaborators, have for yeast growth rates undergoing diauxic shift.

These findings help to demonstrate that group expectations for judging correct findings play a pivotal role in advancing scientific understanding. The idea that scientific knowledge is waiting to be discovered, hidden gem-like in the mysteries of the natural world, is shown to be problematic when so much of the work to define scientific knowledge is done through group agreements and shared expectations (Bloor 1991, Barnes, Bloor and Henry 1996). For Rosalyn and the RL team, automation is one more tool that they use to test these shared expectations. One possible way to think about automation and experimental space is that it is not the outputs and data analysis completed using automation that results in an expansion of experimental space. Rather, it is the collective agreement among groups of researchers that automation tools are acceptable methods for experimentation that enable this expansion. In this way, automation tools are an expansion of the epistemic infrastructure when researchers

agree that they can judge the results they produce using these methods to be good enough.

6.9.2 Designing the 'lid lift protocol'

Deciding whether samples were growing as they should involved instances when Rosalyn and her collaborators suspected that too little oxygen was getting to the plates. As described in section 6.7.2 above, a major advantage of the robot platform for Rosalyn and the RL team was the ability to incubate and measure the growth rates of samples at set intervals for long periods of time, up to 42 hours consecutively in some cases. However, the initial results derived from these extended periods of growth and measurement were not satisfactory for the RL team. The research team were confident that the yeast strains and conditions they were using had been successful in showing diauxic shift in previous published work. For several weeks the growth rates captured using the robot platform for incubation and measurement did not have clear periods of growth, plateau and growth, as Rosalyn and the team were looking for. Rosalyn suspected that not enough oxygen was getting to the samples on the plates, and that the plate lids may have been a factor in this. Removing a plate lid and leaving samples exposed to air in the room was a straightforward task if completed manually, however Rosalyn wished to continue using the robot platform for measuring growth rates at set intervals over extended periods of time. To achieve this Rosalyn set about designing new steps in the incubation and measurement of samples and built in a 'lid-lift protocol', as described above.

To understand the difficulty in using a robot arm to remove and replace a plate lid it is worth considering how Tic-tac and Merlin, the robot arms grasped plates to move between different machines in the automated platform. At the end of the robot arms are two padded grippers that are located at the end of two prongs. Imagine a set of football goal posts lying flat on the pitch before a game. Before the goal posts are hoisted into position, from above they resemble a square horseshoe. The padded grippers are located on the inside edge, at the end of the goal posts, farthest away from the cross-bar. Taking hold of each plate and moving it from one part of the platform

to another required the grippers to be closed on to the sides on the plate with enough force to lift it. Force from either side of the plate needed to be in–balance so that the plate remained level and did not spill any liquid during the movement, and the force also had to be low enough to ensure the grippers did not crush or crack the plate.

All of the above calibration was monitored and adjusted by the RL team regularly, and often when the system failed and stopped operations unexpectedly, it was related to some form of error in the gripping and moving motions of the robot arms. To introduce a new step in the system process, one that could grip a plate lid without taking hold of the entire plate, remove the lid, place it in a different location, then return the lid to the plate after a set period, was immensely challenging for the RL team. They spent many hours trying different grip pressure and adjusting how far down the plate the grippers should be set to take hold of the lid. Rosalyn also replaced several sets of grippers because she believed the rubber pads were marginally different in their thickness, causing the robot arm to replace the plate lid at an angle, which caused further failures during the next step when the entire plate and lid needed to be moved and returned to the incubator or plate reader.

Clearly to use a thumb and middle finger to remove a plate lid is not the same as using a robot arm and rubber gripper. However, in deciding on correct pressure and placement of grippers Rosalyn did use her sense of touch and the way her hand moved in space to keep a plate lid level and in the correct position. Importantly, when using the robot platform Rosalyn's decisions about whether or nor her yeast samples were growing correctly were also influenced by whether or not the robot arms were handling the samples in the correct way. Often, this was not a matter of finding one optimal setting and fixing this in place for all future operations. The interplay of the RL team's judgements of correctness, and the behaviours of the machines and cells they worked with, meant that Rosalyn and the RL team generated confidence in their results through the ability to adjust and tweak those parameters.

6.9.3 Thinking with foot stools

It was because of this need for continual adjustment and tweaking that Rosalyn and the RL team kept rulers, spirit levels and marker pens close-by. To try different gripper positions and plate movements, Rosalyn needed to stop and start operations from the safety of the computer workstation, and then 'climb-in' to the robot platform to look closely at the way the grippers took hold of plates and lids. Because of the height of the bed and the fact that all the machines were arranged around the perimeter of the platform, facing inwards for the robot arms in the centre, Rosalyn needed help to reach the centre of the system. This help was provided by a foot-stool very similar to those found next to library bookshelves. This seemingly mundane object in the laboratory was actually a key tool for Rosalyn and other members of the RL team. The foot-stool changed the EMA platform from a system designed to be closed and served automatically by Tic-tac and Merlin from the inside out, into a system that was open to Rosalyn and her collaborators.

There is much talk about robotics and automation as chiefly about 'augmenting' (e.g. Parasuraman, Sheridan and Wickens 2000) the human body and enabling humans to do more than our physical limitations will allow. However, the design of the EMA system meant that Rosalyn's physicality, her height and forms of movement restricted her ability to apply the necessary adjustments and tweaks required to keep the system functioning for the team's needs. By having the foot-stool close-by and using it to make the EMA system accessible to her bodily form, Rosalyn was introducing a kind of 'system hack' that opened up the EMA set-up to better fit the design to suit her particular, embodied needs. Wajcman (2006) sees an infusion of an image of masculine 'mastery and non-sensuality' in her analysis of hacker culture. In some ways Rosalyn and other embodied human operators needed to hack the EMA system to better fit their physicality. The foot-stool was a symbolic object that was always present in the EMA laboratory room, demonstrating the regular need for modifications to the system to suit users' bodily needs. It was only by being able to intervene in this way, and using her bodily knowledge that Rosalyn could have trust in the results from the robot platform. Linking this to Wajcman's discussion of gender politics and non-sensuality and mastery as forming part of the masculine hacker identity, the robot

platform initially promised, in policy narratives at least, mastery over the complexity of biological understanding. In practice however, the operators of the EMA system needed to twist and contort their own bodies to better fit with the design of the system, and users needed to develop a fingertip-feeling for robot and cell behaviour. Therefore, the platform does not stand as a straight forward extension of this idea of masculine mastery over the biological world. This is because although the system design imposes constraints on the right type of body that can operate the platform, sensuality is also crucial to developing an embodied practice and the fingertip-feeling required to maintain functionality.

In the next two sections I move on to further promissory narratives expressed in the policy documents of Chapter 4. These two final promissory narratives relate to the specific economic arguments that policy makers put forward for laboratory automation and synthetic biology, particularly the promotion of research competitiveness and increasing commercialisation.

6.10 Automation will increase technological capacities (Narrative 4)

One of the major drivers for investing in new automation facilities for the biosciences, found in the *Biodesign for the bioeconomy report*, is to create infrastructure on a national level. A major attraction for selecting the RL as a case study site was that the research team held international recognition for developing world-leading expertise in using robotics in the biosciences. However, the pinnacle of this recognition was now some years in the past and the research team had gone through several phases of research grant and personnel changes. Even the automation platform was now re-designed and re-named from the initial design and publication records. For these reasons, the facilities at RL seemed to be off-radar for bodies like the SBLC as the investment decisions and research funder aims for the RL platform were now difficult to pin down, and certainly could not be traced clearly to a concerted policy effort at developing an internationally competitive research facility. The laboratory PI, Kieran helps to explain the mixed fortunes for his platform:

> At one point we were having difficulty getting grant income to do more … work [with the robot platform]. We're reasonably OK at the moment but after the article in *Science* we didn't get any funding for a number of years which was not what we expected. … You know, we had all this publicity, it seemed really good but we couldn't get any grants. (Kieran)

Kieran goes on to describe his experience of feeling on the outside of the synthetic biology core, and explains his frustration at targeting opportunities in this area that could have utilised automation, only to be unsuccessful in securing the large grant funding opportunities associated with the field. Eventually, Kieran looked to the United States and received funding from DARPA, and to Europe for funding from the European Commission. Each of these projects forming part of large international research consortia that spanned disciplinary boundaries, including: text mining, computer science, and molecular biology. It is notable that, located in the same building as the RL is a large synthetic biology research centre, and that Kieran and his team do not seem to overlap in terms of their day-to-day work with this centre, despite both laboratories having a keen interest in the use of automation for the biosciences.

This is not to say that UK academic biosciences are not full of research teams working in close proximity that have little contact with each other in their routine research concerns each day. What seems important about Kieran's explanation of his team's fight to keep their platform relevant and operational is that he was fully aware of the synthetic biology community and the potential for automation development in relation to this, but that he felt excluded in some way from this community because he was not 'part of the club' (Kieran, Interview 27/07/2016). These findings suggest that the technical superiority, or perceived inferiority of a system, even a system implicitly endorsed through leading academic journals, requires something else to succeed, and to stay relevant. In many ways this observation is central to the idea that any system is engineered socially as well as being engineered to meet technical aspirations; in this way all technical systems are 'heterogeneously engineered' (Law 1987).

6.11 Automation will enable further opportunities for commercialisation (Narrative 5)

Perhaps because the RL was on the periphery of the more recent large-scale investments in automation facilities in the biosciences, it is unsurprising that I encountered little reference to commercialisation agendas during my time there. The system was originally set up with the aim of becoming a proof of concept for the potential of automation to systematise experimentation, and to use machine-learning to help generate novel hypotheses. In later incarnations the system was repurposed to use machine-learning and automated experimentation to find novel uses for existing compounds. One of the major publications for the system users was the use of EMA to identify a novel use for an existing compound in the treatment of malaria. The commercialisation of this kind of work is of course possible, but this was not what the EMA system builders and users were focused upon, and did not form part of the expectations of the funders of the system over time. A similar analysis can be applied to the current work on yeast diauxic shift, which has many potential applications in developing drugs to treat tumour growth. Again, Kieran and the EMA team were trying to demonstrate the potential for automation to enable these kinds of developments, rather than proposing ways they could use automation for the commercialisation of such products in the future.

A key observation at RL compared to my subsequent case study site was that the EMA system, in its current form, represented the most recent incarnation of a system that users and designers had adapted over a ten-year period. One of the implications of this for the current RL team was that many of the original service, maintenance, and consumable contracts had long since expired. Additionally, for Craig, the current RL computer programmer, many of the earlier system design iterations had not been well documented and he had daily anxieties about making changes to the system setup which could affect an operation that would be difficult, if not impossible, to reinstate. Performing a system upgrade was high-risk because there would be no guarantee that the existing integration setup would be operational afterwards. In addition, they did not know whether this upgrade would require the team to also upgrade the specialist automation software used to control the robots. Such an outcome would be

prohibitively expensive for the RL team and was not something covered by their current grant funding. Craig bemoaned the way that specialist software suppliers have a captive audience once one commits to using their systems, and can charge very high prices that become harder to avoid as the system ages and any initial service and maintenance contracts end.

6.12 Conclusion

Researchers at RL take accepted scientific knowledge about yeast diauxic shift and use computer hardware and software (automation tools) to replicate findings and generate new data. The purpose of using automation tools is to speed up the data gathering and analysis processes and to show that humans using computational tools are better at creating scientific knowledge than those without such tools. Seen in this way, the intended role of automation at RL, especially for Kieran, the laboratory PI is to promote consensus-building for the need for computational tools in the biosciences. The automated systems also promise to reduce the costs of research programmes by removing errors and applying machine-learning to create more accurate predictive models for general cellular organisation. Finally, the robot platform is also designed to capture and record steps in the experimental process to enable a standardisation of protocols and more efficient sharing of methods and results across time and space.

The team recognises that humans and robot systems work in combination and refer to the superhuman strengths of robots and machine-learning for completing tasks quickly and accurately. My time at the RL has focused not on the limitations of humans but on the actions that humans perform which are integral to the smooth running of the robot platforms every day. In this chapter I have demonstrated that rather than viewing experimental work as a division of labour between humans and robots, the lived experience of laboratory users is one of adaptive decision making based on the specific nature of the problems faced each day. General theories and experimental hypotheses drive the research along, however the machines function and the yeast behaves in unexpected ways.

One perhaps surprising finding from observing the RL team’s work was recognising that their theories and hypotheses were not abstract intellectual thought exercises.

Rather, for Rosalyn and the RL team to have confidence in the results coming out of the experimental work, they needed to engage their body fully in that work. Rosalyn's judgements and decisions needed a bodily engagement with the EMA platform, and a haptic-sensual understanding of how that platform can be made to encourage cellular growth and yeast behaviour in line with hers, and her colleagues' expectations about the right growth, and the right conditions. These findings further emphasise that embodied tacit knowledge is crucial to both increasing understanding of biology and to increasing the range of tools available for generating that understanding – researchers' epistemic infrastructures.

Knowing how to keep the workflow moving also involves Rosalyn retaining membership of multiple knowledge communities, including past and present users of the system: programmers, cell biologists, and technicians as well as other knowledge communities, including university building users, admin and support services, instrument makers and service engineers. Understanding how these various interconnecting communities have shaped the EMA system design over time has been a particular challenge for my work at RL. The past uses and decisions about the way the system should be run have often been passed between users in ad-hoc and hard to trace ways. The legacies of a decade old system are not just questions about operating systems or operating instructions. As the chapter has shown, such apparent technical choices are infused with the social, political, and economic concerns of different groups of users. My findings about the centrality of Rosalyn's and the RL team's physicality for knowing the EMA system, and knowing when to trust the results that come from it, convinced me that any passing over of corporeal knowledge, or 'fingerspitzengefuhl' (Mackenzie, 1999: 426) risks impoverishing an analysis of correct functioning of automation in the biosciences.

The next empirical chapter explores the set-up considerations for a newly designed automation platform in the biosciences, and takes up the theme of different knowledge communities in the making of a successful system.

CHAPTER 7:

Living a double-life with the Assemblers Lab

"We are not academia, as such." (Tilda, Laboratory Manager AL)

7.1 Introduction

When I first identified the Assemblers Lab[7] (AL) as a possible case study site, I felt extremely fortunate to have found a centre in the making. Not only was AL right at the beginning of its journey setting up a new automation platform in the biosciences, it was part of the wave of new capital infrastructure that the SBLC was promising would revolutionise the biosciences. AL's fully-automated system was an ideal candidate for comparing promissory narratives and lived experiences. Being at the start of the centre's set-up also came with some challenges. As described in Chapter 3, I secured only conditional access to the AL team, and because of this relied more heavily on informants' accounts during interviews to understand their experiences. Furthermore, because part of AL's set-up involved partnerships with external companies, the AL management team was understandably cautious about giving me permission to observe and record its work: even if the AL team was fine to share everything warts and all, their partners may not have been. In the end, this difficult start to the case study at AL provided a potentially radical insight: perhaps the AL team was building a new model of how to be academics in the biosciences. For Tilda, the laboratory manager, AL was '… not academia, as such.'

I open with Tilda's quotation because of the way she herself described her formative career in the biosciences, coming from a background in technical operations in the dairy industry, via a technical post at the European Molecular Biology Laboratory (EMBL), and finally to the UK to study for her PhD in an academic laboratory. Now that Tilda holds a PhD and has significant publications and experience within world-leading research laboratories, this latest role as Laboratory Manager for AL seemed at first to be a significant change of direction in her career. As the sections that follow demonstrate, Tilda's responsibilities as Laboratory Manager were multiple and

[7] I use the Assemblers Lab as the pseudonym for Case Study 2, a DNA assembly centre based within a UK academic university.

involved aspects of business planning, human resource management, supplier negotiation, project management, academic networking, and public lectures. However, Tilda's interests in creating efficient systems for research methods, rather than conducting that research herself did have some antecedents.

Tilda's previous laboratory's PI moved to another university for a new post and she was left with a range of under-utilised automated machines. By recognising the timesaving potential of the automated colony picker, as one example in her former PI's lab, and then beginning to charge other researchers to use it, Tilda was pre-empting the model AL later wanted to expand by creating a fully automated DNA synthesis centre. Listening to Tilda speak about the goals of AL and learning about her career history helped me to understand some of the tensions that came up in my interviews with the rest of the team. The AL team was a diverse group, with backgrounds in cell and molecular biology, computer science and engineering, critical design, and in Tilda's case an interest in developing tools and services for other scientists. Most of my informants held PhDs of one kind or another and each person I interviewed had an understanding of the field of synthetic biology as an academic discipline. However, as Tilda explains, the purpose of AL was not academia as might traditionally be understood, producing publications and advancing specialist knowledge claims:

> They [publications] might happen if we set up new methods and we can publish them, we of course will do that. If we have collaborations where people put us on their papers, we will not say no either and who knows, maybe they [publications] will happen a lot and maybe some [people] decide to go back to academia but we are not academia as such. They [staff] cannot come here to work on their publications because we are here as a service; we have to deliver the product and nobody can fiddle around there with their experiments and not do the assignment for the customer, no.

In this description of AL, I find the main questions that emerged from this case study site. What are the boundaries between research and technical staff? How are expectations different when automation researchers conceive of their work as separate from another aspect of scientific or engineering practice, and what issues of identity

might result? Finally, and perhaps most crucially, in what ways are automation technologies seen as orderly and serious, in contrast to a more playful 'fiddling around' with experiments in a research laboratory as traditionally conceived by Tilda above, where the language of a customer makes less sense? The way Tilda posits the work of the AL is by comparing its business-like approaches to customer service with a more unstructured and intangible idea of scientific work. The example of creating publications is relevant here because, for Tilda, publications are an added luxury that might be possible as the AL meet customer needs, but the real work of the AL is to be a service that delivers a product.

However, as my time at AL progressed I found that Tilda's goals had multiple interpretations among the team, not least in respect to what their 'product' actually was. Creating large fragments of bespoke DNA would be the simplest description of the AL's product. However, as I go on to demonstrate in this chapter, for the AL team to create those fragments they needed to understand why other researchers – the customers – needed to build their samples a certain way, and what types of analysis other researchers would carry out now and in the future, using those fragments. The AL's product, therefore, was also the requisite expertise in how its platform could work for those context-specific needs. Furthermore, establishing and maintaining that expertise involved the AL team knowing how it could make the platform flexible enough to continue to be useful as those customer needs changed and researchers' analyses moved on. The line between customer and collaborator, in this view, was often blurred. The main empirical work in this chapter deals with these various blurred lines between academic and business-focused priorities, and how those boundaries are constructed in language use. I go on to conclude that the AL team lived double lives as it crossed various rhetorical boundaries in its descriptions of automation in the laboratory.

7.2 Aims of the chapter

The data presented in this chapter plays on this concept of being something, but not quite being that thing at the same time. Thinking again about the meaning of 'amphibios,' to live a double life, informants at AL had to make choices when describing the most important aspects of their work. Sometimes these aspects seemed

clear, as for Tilda above when speaking of the AL team writing its own publications. However, often the descriptions informants offered of their work at AL crossed boundaries between being focused on providing a service to other researchers, and needing to collaborate closely with those researchers to know how the automation system could be adapted to meet their needs. In this way informants at AL were being something (e.g. a service provider), and not being that thing at the same time.

As I go on to describe in the concluding parts of this chapter, Ian, one of the automation engineers at AL, stated repeatedly how different his role was from someone who just pushed a button to work a machine. Ian derived value from his in-depth experience with the AL setup, and one of the main ways he expressed that value was by contrasting what he was doing with what others were not doing. Ian, in short, was engaged in forms of boundary work (Gieryn 1983, Gieryn 1995). He wanted to firmly distance what the AL team was doing from what he saw in other areas of laboratory automation. Ian described other forms of automation in which users "just pressed go at the start of the day". The idea that the AL machines just required the push of a button to function was laughable for Ian because he and the team were invested so deeply in adapting the machines to work effectively for their purposes. The central aim of this chapter is to show how talk about the real work of developing automation for the AL team was part of a rhetorical game of inclusion and exclusion in Gieryn's terms. However, the AL system users needed to be inclusive and exclusive across multiple boundaries and at different times and places as they navigated the various demands of being a newly funded large DNA synthesis centre with lots of visibility in their field of synthetic biology. To maintain these multiple identities, I argue, the AL team needed to live a double life.

7.3 Structure of the chapter

Before exploring these issues through analysing conversations with different AL team members, I first present ethnographic observations from the early phases of the case study. These observations shaped my subsequent thinking because I entered the AL at a time of intense activity. I engaged in multiple conversations with key informants as they were in the process of transitioning from one workspace to another, and as they were beginning to reflect on the AL's status as a paid-for service provider that would

become a business unit independent from a specific academic laboratory. These experiences helped me to tie in seemingly contradictory accounts of what the AL was, and what it was going to be in the future.

7.4 Observations of a centre in the making

During the spring of 2016, I arranged my first visits to the AL. The AL team was in the initial setup phase during this time. Tilda was in post as the manager, an automation engineer, Charlie, worked with the laboratory PI, Carl and was responsible for testing and buying equipment and the automation specialist Alex was starting to programme liquid handing robots. There were another four months until the official opening of the AL however, and the main platform room was still under construction. The location of my first official visit was a small shared office, where all of the current AL staff had workstations or desk space for a laptop. Opposite the office was a temporary laboratory room with several pieces of equipment on desks and benches, and a larger liquid handling robot in the centre of the space the AL team was using. Alex was busy in this room working with the robot.

When I arrived for the first day visit, I entered the shared office, a cramped space with six workstations in a room designed for three at the most. The office space and laboratory room opposite was temporary. I introduced myself and found a free chair to wait for the AL Manager Tilda. On arrival she explained there were a couple of tasks to finish off, and then we would go down to the newly built suite on a lower floor to talk about my interests in the AL. Before we went down, I noted how busy Tilda was, dashing from one task to the next, taking calls on her mobile phone, organising both internal (staff) and external (supplier) arrangements. Tilda showed the way and we walked down the two floors to a newly built office suite, directly beside the under-construction AL centre. There was a full-height glass wall separating the two rooms and each of the remaining walls was painted in brilliant white. We settled in to sturdy new office chairs and I asked about the AL, with the smell of fresh paint filling the room.

There were two people in polo shirts inside AL room, seemingly installing various pieces of equipment. Tilda told me the two people were engineers, and that they were on-site as part of an integration contract AL had with a large instrument supplier. This supplier was to take on the complex tasks of installing equipment (not all manufactured by them) into a linear robotic assembly line. Later I asked Ian, the newly hired automation engineer, why this supplier was able to take on the task of installing and linking together, equipment that is not owned or supplied by them. He said that the integration company was large enough to negotiate with other suppliers to get access to their setup protocols, which are inherently commercially sensitive, and almost impossible to get without the kind of leverage a large, well-funded manufacturer can bring. The integration company was using an overarching software that would allow all the pieces of equipment (which have their own proprietary software) to 'speak' to one another.

In a later interview with Ian, I asked about his background and how he first became interested in automation and biology. Ian was awarded his PhD in cell biology from the same institute that was setting up AL, and he conducted his experiments in the same building where we met. The AL leadership advertised the automation engineer role several months previously, and Ian took up the position on a temporary basis to cover for Charlie who had left for a period of maternity leave. Ian put his successful application down to his long-time interest in coding, previous employment as a software programmer, and current knowledge of biological experimentation methods. During the interview, Ian was keen to stress the importance of personal preferences when setting up an automated system for the biosciences. He explained that, although he did not choose or evaluate most of the equipment, his job was to 'make the kit work'.

As we returned to the small temporary office upstairs, I sat in one of the chairs waiting to go for lunch with Tilda, Ian and a few members of the team. There were several calls coming in and going out to one of AL's instrument suppliers about an imminent move of one piece of equipment out of the existing space and into the new AL space downstairs. Ian and Tilda were negotiating with the contact at the supplier. They needed guidance on how to safely lift and move the liquid dispenser without affecting

the calibration. The planned move was booked in for that afternoon. After establishing what he needed to disconnect, in what order, and what (if anything) he needed to fix in place, Ian seemed happier, and said he now felt slightly more confident about moving the equipment without official support from the supplier.

Tilda wanted a representative from the supplier to come over at some point, after the move, to test that all was working correctly. This was complicated however because AL no longer had a support contract with the supplier, so getting someone out for this purpose would have been prohibitively expensive. The idea was for someone to call in next time an engineer was on-site for another reason, though Tilda could not really say this explicitly: it needed to happen under the radar. I observed Tilda and the service engineer at the supplier as they spoke in a kind of code. Each person seemed to know what the other wanted, and would have been willing to help, but both talked around the issue because both Tilda and the engineer were constrained by the expectations of their respective organisations.

During the rest of my time at the AL, I noticed that Tilda and the team were constantly negotiating these institutional expectations. Tilda joked during my first interview with her that senior leadership kept pushing her to complete a business plan for the AL, but that no one in the leadership team could tell her what a business plan should look like. Tilda eventually decided that she would need to decide this herself, and for what range of costs and system utilisation targets the AL team would aim. Tilda achieved this breakthrough by seeking advice from a professional coach who helped her to break down the plan into manageable sections. Here Tilda's role as laboratory manager also included aspects of business process planning. However, it was Tilda who had to be the one to translate the strategic high-level objectives of university leadership (e.g. to create a commercially viable DNA synthesis service) into day-to-day details about what use of each machine should cost per hour.

I could see her grappling with these various challenges as we spoke during interviews and I came to understand that many of the details in the business plan were arbitrary figures because of the inherently speculative nature of what the AL leadership was asking Tilda to do. How could Tilda say exactly how much they should charge a

customer when the team's time allocation to various projects was impossible to determine in advance of working with those different customers and understanding their specific needs? A further complication came from the fact that Tilda, Ian and Alex had yet to adequately understand how the service they provided would be utilised by different researchers. For example, would the bespoke large fragment DNA synthesis become the core activity of their work as indicated in the funding proposal? Alternatively, would the team also provide various automated provisions for other researchers by completing colony picking or PCR services using the automated platform? This latter aspect of automation connects to promissory narrative one, outlined above, around automation replacing some aspects of wet-lab bench work to speed up tasks and free up researchers from highly repetitive processes in their work. The AL team was cautious however in speculating about radical reform in these areas because it remained ambivalent about the extent to which automation would deliver on those aims.

For example, during lunch, Ian, Tilda and I talked about automation and the skills needed by contemporary biologists as they saw it. After initial dialogue about promissory narratives that suggest all laboratories will be more automated in the future, Ian commented that he was not so sure. For him, automation featured very little in his PhD because the work he needed to do was not highly repetitive. Ian suggested that some kinds of work will become more automated but others will not. This conversation led us on to a discussion about the rise of centralised DNA assembly centres, and the possibility of becoming a service provider to other laboratories, both internally at this university and for other universities. As described above, in later interviews it became clear that Tilda was aware of expectations around creating a business, devising costings estimates and a business plan for charging to use AL's services. However, during this initial lunch with the full team the idea that the AL was to become a service provider seemed a secondary priority to getting the system up and running.

After lunch, I went for a tour of the new AL suite and passed through a door in the glass wall to observe the whole platform. Ian explained what each machine was for and how the team had positioned them to allow three robot arms to link each one

together as part of the automated setup. It was striking how similar some of the machines were to machines I observed at my previous case study site, given that RL is not a DNA assembly centre. There were certain larger liquid handling robots that I was not familiar with, and several additional machines that I was seeing for the first time, including a plate-sealing machine that researchers used to fix semi-porous temporary films over plates containing samples. I later reflected on the functionality of a plate-sealer and how this compared to data from my other case study with the RL. As I described in the preceding chapter, Rosalyn and the team devised a 'lid-lift' protocol when they thought that samples were not being exposed to enough oxygen for the expected diauxic growth rates. For the RL team the lid could be either covering the plate or not covering the plate and the protocol they designed used robotic arms to remove the plate lid and replace it again after set periods. The AL team clearly also recognised sample exposure to oxygen would be important for their experimental work and used the plate-sealer to simultaneously protect the samples from contamination and allow some air through from the external environment.

Initially, I imagined that having a similar plate-sealing machine in the automated set up could have been helpful to Rosalyn and the RL team as they tried to ensure more oxygen got to their yeast samples. I wondered if this machine would have stopped Rosalyn designing a lid-lift protocol. Of course, it was impossible to answer this definitively; however, it was important to keep in mind that Rosalyn adapted machines and processes in response to confidence in the results she was getting. The availability of a plate-sealer similar to the one at AL would only have changed Rosalyn's actions had the results of the experiments been different. In all likelihood, getting just the right amount of oxygen during each experimental run would have called for adaptations by Rosalyn, by increasing or decreasing the amount of time that the plate remained covered, either by a solid plastic lid or by a semi-porous film. These observations and reflections helped me to compare the differences in available resources at each of my case study sites. I began to think about how users at each site needed to adapt their systems to meet their needs and to make those adaptations within their available budgets. As I have intimated above, researchers' actions were usually linked to judgements about correct results.

Having more resources and newer equipment can influence the tools used to make those judgements. For example, adjusting sample oxygen levels using a plate-sealer rather than a solid plastic lid and robot arm. However, judgements about acceptable growth and theories for promoting growth come from discussions between researchers and their knowledge of previous work in the area. The RL team used 'lid-lift' whereas the AL team used a plate-sealer but both teams utilised their immediately available resources and chose their methods in response to the behaviour of their cells. It is important to understand this point clearly. What made my informants amphibious researchers was their intimate knowledge of the behaviour of their cells and their ability to control their experimental processes using the tools available in each particular system set-up. Keeping track of the latest tools and newest equipment mattered less for these amphibious researchers than having an intuitive understanding of their own particular system's quirks and limitations.

Every system user was working towards similar goals of understanding biological complexity or building large DNA fragments for specific research interests. However, each user also needed to develop an understanding of the complexities of automation tool capabilities, and have a good sense of how they could make those tools serve their current and future needs. The AL was in a fortunate position of being able to purchase new equipment and therefore it designed and set up a system that included as many different tools as possible that could aid its work. During my time at the AL, the team was in the process of becoming familiar with those tools and had yet to test most of the potential applications for the system through repeated use. I now go on to describe this system set-up and some of the ways that the AL team tried to envisage the future needs of system users.

7.5 The AL space and observing the initial set-up

The AL room was long and relatively narrow, so the automated bed ran in a kind of L-shape and took up approximately two thirds of the room. The other third of the room looked like more conventional laboratory bench space. Ian told me that they used some of the conventional laboratory space for electrophoresis. For the automated set-up, it did not make sense to try to include electrophoresis as part of the L-shaped automated platform because the machines that were on the market at the time were not designed

to be compatible with robotic arms. The AL team decided to leave spaces in the automated assembly line to accommodate newly available technologies, so that they could accommodate the development of robot-friendly electrophoresis machines (if and when available) into the system in future. There is something striking about this observation that the AL team tried to future-proof the machine set-up to accommodate potential new tools coming on to the market. Not only did the AL team need to make existing equipment work for their purposes, it also needed to try to predict how well this existing equipment would work with as-yet unavailable tools. Such was the ambition of the AL system designers that they wanted a system that could meet the needs of currently practising researchers as well as a system that was flexible enough to accommodate and even shape those needs in the future.

I returned to AL about a month later to observe the integration engineers conducting a number of load tests. The engineers from the integration supplier were not the same as when I had last visited. The integration supplier is an international company and the first two engineers I met had now returned to their head office in North America; the new engineer was at AL to finish the setup. Ian had mentioned that discussions had taken place between AL management team about getting what they had paid for from the integration company. The integration contract stipulated that AL would have access to a dedicated team for initialising the system and there had been some doubts about whether this was the case. However, overall the AL team had felt able to communicate with the integration company and to work together to trouble-shoot problems with the system set-up.

All of the set up activity described above was working towards a final ‘site test’, in which all of the equipment was to be user-tested and handed over to the AL team in order for it to manage and conduct planned work. This was a crucial time for the AL team and there was an urgency about how Ian was moving around AL laboratory space. Tilda was also concerned about the increased workload the AL was facing during the site test. For this reason she asked that I suspend observations during this two-week site test period. I certainly experienced an elevation in anxiety levels since I had last visited, and the AL team seemed to have less time to chat informally as they prepared for the site test. Clearly, there are multiple reasons why Tilda and the AL

team had concerns about having an external visitor in the laboratory making observations during this crucial site test period, including the desire to protect each team member's time. A further reason I deduced for this apparent caution was that the AL had established commercial business partnerships with a software company in the US. Each day at 5pm, the team would have a Skype meeting with this company and the AL team asked me to leave the office before 5pm to allow them to conduct the meeting with only team members present. With business like customer-facing approaches then, also come restrictions and anxieties around commercial sensitivity. It was unclear if the software partner made explicit demands on the AL team about external partners, but my experiences suggest that partnerships with commercial providers do influence how academic laboratories view other academic colleagues, and how cautious teams are with their information.

As well as partnerships with a software company, the AL team also needed close collaboration with the integration company. In a later interview, Ian discussed this collaboration with the integration supplier, and identified how crucial his own knowledge of biology had been for getting the system to function correctly for him and the planned projects for the AL team. There was an important difference for Ian between agreeing that the system was working and agreeing that the system was working *in the right way*: '…when you look at any of the machines you ask yourself "mechanically could the machine do this?" That's one answer but then you have to ask yourself scientifically does it make sense for the machine to do it this way?' This judgement of correct functioning by Ian recalls Rosalyn's judgments about correct results. As I discussed in the previous chapter, Rosalyn and her team sat and discussed the shape of the growth curves in their diauxic shift experiments. These discussions helped the Rhodes Lab group decide if the machines were functioning correctly. Ian and the AL team similarly considered correct functioning to require judgements of correctness based on how well the system conformed to their established patterns of good experimental practice, including the need to be sensitive to effects from changes in temperature.

Another task Ian was responsible for was looking after a tour group of 16-17 year old high school students. The university had given these students offers to study there as

undergraduates. Ian's demonstration of AL facilities was a clear pitch to these undergraduates and his descriptions of the potential of automation seemed aimed at influencing their choice of university in the coming months. Ian set about explaining the value of the equipment at AL, and compared this to when he completed his PhD. The focus was on the timesaving capabilities of automation. Ian explained that they had design the AL equipment to be 'walkaway', before pausing and adding 'at least in theory' [laughs]. This acknowledgement of a difference between what the AL system was design to be, and how it worked in practice appeared as a momentary joke during an otherwise positive appraisal of the system benefits. I understood this joke to be a genuine moment of honest reflection by Ian that he quickly passed over as he moved on with the tour. Clearly, the expectations for full automation were implicit in the AL's presentation of their systems but when the audience contained a mix of experts and novices in the challenges of laboratory automation Ian and the team used humour to bridge the gap between the promises and the lived experiences for automation in the biosciences.

The tour covered the system set-up, which Ian said they had designed to be like Lego, that is, highly modular. Ian ran through a list of the equipment on show: polymerase chain reaction (PCR) machines, liquid-handling robots, machines for colony picking, a centrifuge, cold storage, plate readers, an Echo acoustic dispenser, a plate bar code reader and a plate sealer. He explained that they controlled all the devices centrally through workstations and interfaces, allowing a smaller number of users to conduct a larger range of tasks, often in parallel. Linking this to potential student benefits, Ian explained that students at a university with larger laboratories and sophisticated facilities would have options from a wider range of research projects. Therefore, for final year undergraduates there would be plenty of choice for the four-month placement at the end of their studies. I reflected on this episode after later interviews with Ian and it was striking how different his accounts of the value of automation were when explaining it to potential undergraduates, and when explaining it during our interviews. Perhaps though, this is not so surprising because the expectation from the university, for the AL team, is to promote a positive vision of the AL, and help the

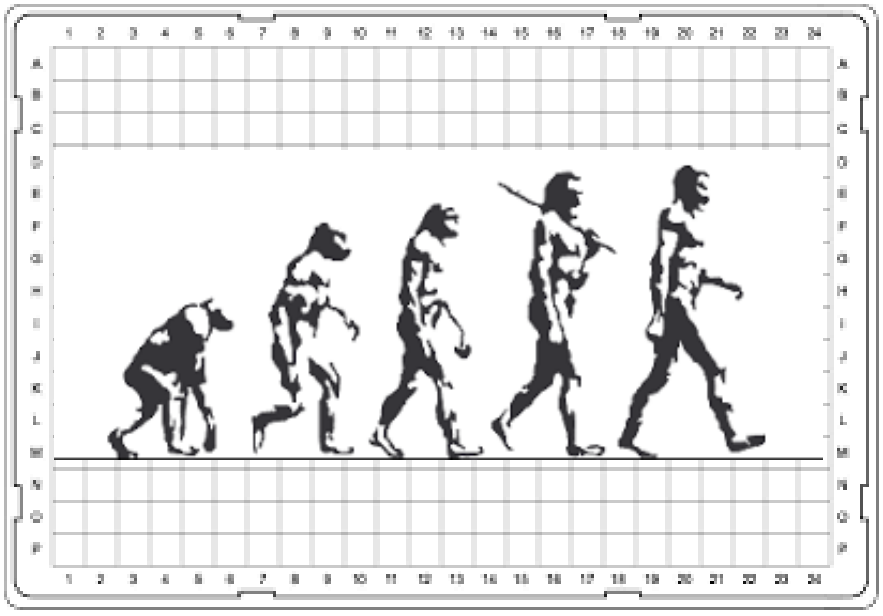
university to remain financially viable by encouraging more students to enrol on courses.

Two professors who were not part of AL accompanied the students. The professors were largely quiet during the tour but moved around with the groups of students to listen to Ian talk about AL's equipment. I happened to be with the group closest to the professors and observed a discussion about the range of facilities that AL was developing. The professors seemed surprised about the different pieces of equipment on show and focused on the individual instruments rather than the robotic arms, which had been a central focus of much of the tour. The general conversation between the professors was one of coveting some of the equipment in AL. After the tours had completed, I again asked Ian about becoming a service provision to other laboratories in the university, mentioning the interest of the professors during his tour talk. The answer, again, was that AL was not capable yet, but this was something for which they would be aiming.

Two days later the AL manager Tilda gave the first official talk to the rest of the institute in order to explain more about the work AL were doing. The academic manager for the institute supported AL, and pitched in at different points during Tilda's introduction to offer thanks to all those involved in the AL set-up for their hard work so far. This wider institutional support did suggest an awareness of AL as something the wider institute should promote and utilise. I reflected on this episode later and recognised that the success of the AL was more than partially dependent on communities of researchers sharing their understanding of the AL service through similar profile-raising exercises as happened during this talk. The AL team was engaged in building a brand for its service, as I outline below, however the clearest potential market for the AL during the initial phases was the groups of researchers within their own institute. I conducted two follow-up interviews with attendees at these institute events, and found that one researcher already had access to a liquid-handling robot, and another researcher described her work as not amenable to the tools of large-scale automation. The communities of researchers around the AL were varied and the value of an automated DNA assembly service was yet to be widely shared.

Before Tilda began the talk, she previewed the first slide on the screen. It was an image of a 384 well plate. The AL had designed the plate to show its logo in different colours using each well like a pointillist painting to create an image of the letters representing AL, with a well-known local monument in the background (though I had to ask exactly what it was). Sitting beside and behind me was the rest of AL team. Elisa in particular was keen to show off the (far better) images she had on her phone, including a 384 well plate Alex had produced of the Evolution of Man (see Figure 5 below for the type of image Alex reproduced). Alex used an algorithm to instruct the robots to place different colours in each well. It looked, as everyone agreed, 'really cool'. I suspected that Tilda's choice to use the AL logo, as an example of Alex's robot-plate-imaging method, rather than the more complex and much clearer images of the evolution of man was not a group decision. For Tilda, the quality and uniqueness of the image produced was a secondary consideration, and promoting the AL brand to the wider institute of more value. This perhaps would not have been the team's choice.

Figure 5: Evolution of Man on a 384 well plate



When Tilda began her talk there was a sense that she needed to explain AL's activities to date. The big question Tilda said everyone would want answered was, 'when can we make DNA?' Giving the timelines so far, Tilda explained the drawn-out

procurement process and the ongoing centre construction process. She confirmed how hard everyone was working, and joked that they 'haven't just been sitting in nice new office chairs'. She then gave details of the other institutes around the country similar to theirs, information on funding secured to date and the way this AL will distinguish itself from others by creating larger DNA fragments and offering full automation. The concept of full automation came up repeatedly in later interviews, as I go on to describe below. Thinking back to the policy and vendor promises about automation for the biosciences, many vendors and system designers in laboratory automation were moving towards an idea that full automation was not just difficult but undesirable. Having systems that augment laboratory users in some way, seen in section 4.6.2 earlier, were at odds with the idea of 'full automation' presented by Tilda in this talk about AL's unique selling points. Perhaps in the AL team need to distinguish their platform from other DNA assembly centres in the UK, full automation was a rhetorical promise that helped secure the funding for this centre. In practice, as the AL users pointed out, full automation is almost never going to be the answer for the majority of the work they do.

AL will also offer services from design to fabrication, which brings me back to questions about AL as a service to other laboratories. The policy and vendor narratives about automation promise that the relatively simple tasks of moving liquids around will be quick to automate, and centres like the AL form part of the first wave of infrastructure designed to offer these kinds of automated services to biosciences researchers. In using automated services like the AL, according to the policy and vendor narratives, researchers would be freer to conduct the 'real' academic work of how to design an experiment. However, as my discussions that follow demonstrate, separating out design and fabrication is not a simple task; often the two processes must happen in concert when working with the complex designs and research areas targeted by the AL team. Reflecting on this observation, I wondered if Tilda's vision of AL as a technical fabrication centre, responsible for the production of customers' designs, but not the designs themselves, was still intact.

To underline the effort taken just in physical infrastructure building, Tilda played a time-lapsed video of AL construction. There are three fixed cameras in the laboratory

space, which the AL team installed at the beginning of the build, and Tilda used the footage from one camera to edit a short three-minute version of the construction. At several points, it is clear that visitors to the room are being shown the camera and Tilda picks out a number of well-known faces glancing up as the platform takes shape in the background. The edited film has a rolling credits list at the end, with Tilda named as the producer and others listed for things like the music and editing. This attempt at professionalism and a willingness to step outside of one's area of expertise and become visible in another (that is, filmmaking) suggests that Tilda was also taking the branding of AL seriously, and recognised that the centre will eventually need to view themselves as a professional service.

Having a brand, and thinking about the look of the centre was important for the AL team. The team included an early career researcher from the field of design informatics, Madeline. Although it was not her specialism, the PI tasked Madeline with helping to create the logo for the AL using her design knowledge. The final logo contained references to building and to the lettered labelling of DNA molecules. The AL wanted to emphasise the targeted and bespoke nature of the DNA building service they offered. In a related observation, one of the AL's commercial partners initially rejected an early design for the AL logo because the image was too intricate to be clear when presented on a scale amenable for use as an app (e.g. an application for use on mobile devices). Eventually the AL team adapted the logo in response to the feedback from the commercial partner. I found this level of influence surprising because the AL had autonomy to create their own branding and logos. Having an app to interact with customers seemed an unlikely priority. However, by following their commercial partner's advice the AL team demonstrated their commitment to a future business model in which customers would expect a level of online platform interaction similar to those found when purchasing from large DNA synthesis companies like Gen-9.

However, in later interviews with the AL team both Alex and Tilda spoke of a need to distinguish AL from large commercial DNA synthesis companies. The AL aimed to be like a commercial provider and not like a commercial provider at the same time. In short, their commercial provider status was ambivalent in character. As discussed in section 7.7 below AL simply did not have the staff numbers or resources to compete

with a company like Gen-9. Perhaps the expectations Tilda was trying to temper were those coming from colleagues in different laboratories who were expecting an in-house Gen-9 or Transciptic, with all the associated benefits that customers of those companies had come to expect, including very fast turnaround times for bespoke DNA synthesis needs. The main aim of AL emphasised by Tilda, however, was to enable automated DNA assembly for the institute. As discussed above, Tilda and the AL management team had worked out some costs for providing a DNA assembly service but they were not 'real' costs because everyone was still working on the set up. In the future, they hoped to offer 24/7 operations within the facility, utilising AL equipment to make life easier for all researchers by automating parts of their workload. Again, however, this hope for 24-hour operation was more about the AL team believing this kind of operation was possible using their system, the team remained ambivalent about demand for this kind of service.

During presentations and discussions, Tilda acknowledged the collaborative effort of all the teams involved in the AL set up, the support received from two academic laboratories (the AL was initially a group that belonged in one of those laboratories) and the assistance from the university procurement office. She explained that the equipment suppliers were now finalising the set-up and that the official opening was set for early July, three months from the date of the first presentation about AL to the rest of the institute. AL staff were due to begin their formal training in early May and would spend about six weeks building some DNA. The training I observed was not formal in nature, perhaps because I was not present during the site-testing phase when the integration company were still on site to provide instructions for system operation. However, I did observe instances of Ian and Alex working together to teach each other how to use the liquid-handlers to fill plates with liquids according to specific designs.

For example, Ian would approach Alex with a 'plate map' sketched out on paper to illustrate the appropriate wells that needed specific liquids adding. Alex's task was then to think about how to move the liquid-handler, either by utilising programming scripts he had already written, or by using computing code to write a new script that would move the robots in the required way. Crucially, it was a combination of Ian's sketches, his discussions with Alex, and a continuous effort of talking and testing that

allowed Alex and Ian to get the automation platform to successfully fill and move a plate according to their designs. Alex and Ian reconfigure the policy maker and vendor promises around timesaving and enhanced reproducibility benefits from automation. Through sketches, talking and running simple system tests Ian and Alex spent significant time on producing many different programming scripts and variations of movements with the liquid-handlers to achieve their goals. Although Alex was trying to collate and store common functions for the system operation that could be used repeatedly, a different set of users working on alternative problems would have required a different set-up. In this way, automation might help to standardise certain repetitive tasks but amphibious researchers need a central role in the system build to allow enough flexibility for different research team goals.

As discussed, the AL team needed to repeat some of the robot movements required for different tests. Alex could create a library of scripts that he would utilise again later as part of a common library of functionality. However, Alex's experience described during interview was that of a 'storm' in which he and Ian would work somewhat chaotically to design increasing numbers of small functional scripts for the robot platform, according to a range of problems Ian was working on at any one time. As discussed further below, these periods of storm needed periods of 'peace' to enable Alex to have the time required to organise, label and 'refactor' his library of robot instructions. Re-factoring is a computer-programming phrase that means to take something apart and reassemble it to improve efficiency without changing the external behaviour of the programme.[8]

In later interviews with Tilda, we returned to the topic of timescales and expectations from the wider institute. Tilda was very conscious of overpromising and had experienced first-hand how challenging even the simplest of protocols are to setup on the platform. As well as raising the awareness of AL in the wider institute, I felt that part of Tilda's goal in her institute presentations was to temper expectations and to try to express some of the challenges that remained before AL could become operational. It was interesting to reflect on this observation during later interviews with other

[8] Some synthetic biologists employ this terminology to describe the process of modifying organisms (e.g. Chan, Kosuri and Endy 2005).

institute staff who seemed unconcerned with the progress of the AL, either because they did not use automation significantly or they already had access to the tools they required. Clearly some of the promissory narratives for laboratory automation outlined in previous chapters were penetrating through to some users' experiences and not so for other users of biosciences laboratories. Tilda and her team were navigating this uneven landscape, trying to satisfy the requirements of the investors in their system design (e.g. funders, the University, commercial partners) while generating a 'just-enough' level of expectation to warrant the system's value, all the while not over-promising on what the AL team could achieve in the short-term.

It seemed that on the one hand, AL was pursuing an ambitious agenda to develop a professional DNA assembly service that would operate as an independent business unit, have customers, and become a centralised service provision that modelled how DNA sequencing operated in other parts of the institute. On the other hand, the experiences within the AL called for a tempering of these expectations. As noted above, the AL team recognised that they could not compete with large commercial DNA synthesis companies. An alternative benefit of AL, they argued, would be to ease the workload of colleagues in neighbouring laboratories, perhaps for a fee but not for a profit.

In the initial stages of AL system design the team were not concentrating heavily on these concerns with building an income generating service. Instead, the team were pushing hard to complete the system and work towards signing off the platform as operational. However, as I have already outlined, successful operation means that a system is functioning successfully, and successful functioning requires a system to be working as expected by users like Ian, Rosalyn, Tilda and Alex. In an attempt to have confidence in the AL system functionality, the team worked closely with the contracted integration company to complete the two week site test.

When I interviewed Ian about his relationships with the integration company, he was largely positive. His more reflective comments were not really about assessing the integration company's performance, though, as stated above, this was one topic of conversation among the team. Rather, Ian sought to distinguish different kinds of

engineering, indeed different kinds of engineers that are needed for automation to work for the biosciences. It is through an analysis of these debates about identity that we can see how members of the AL team engaged in boundary-work to build trust and confidence in the functionality of their systems. The next section explores how Ian and the AL team positioned themselves in relation to other areas of laboratory automation.

7.6 Engineering identity and boundary-work

In this thesis, I have argued that amphibious researchers and amphibious working knowledge are critical to designing and operating a successfully functioning automation system in the biosciences. One aspect of this successful functioning is researchers' abilities to navigate and belong to multiple knowledge communities in cell biology and computer science. Furthermore, I have presented the field of synthetic biology as one area in which practitioners familiar with both biology and computing have sought to apply systematic engineering approaches to biology. In the previous sections, I have also discussed how systematic engineering approaches do not mean the same thing to all researchers in synthetic biology. I now use those reflections to compare different conceptions of an engineering identity at the AL. I begin by unpacking Ian's talk about his work alongside automation engineers from the integration company. I then go on to discuss parts of my interviews with Alex and to look at how he compared himself to others in both synthetic biology and engineering more generally.

As discussed in the previous section, the automation engineer, Ian, spoke repeatedly about the different approaches taken by those people who understand science and those people who are engineers 'through and through'. According to Ian, an engineer with a scientific background thinks differently about how to build an optimal automated laboratory than a system-building engineer who is only concerned with creating an efficient system:

> Yeah I mean most of the [integration company] team that I dealt with were engineers by trade, including the PM [project manager] that I was working with. He was an engineer through and through. He didn't understand nor care about the science; it wasn't his job to do the science. It was his job to make the kit

> work. […] He saw everything from a mechanical or electronic or computing perspective so when we laid out the test that has to be performed for system acceptance he and I saw them from very different perspectives. (Ian, interview 05/08/16)

Ian is convinced that, compared to his own understanding of AL system, the project manager and systems engineers from the integration company had different perspectives on what it meant to have a working system. He goes on to give an example where he was attuned to the temperature sensitivities of the sample he worked with, whereas the PM was not: 'If you don't control the temperature tightly enough in this process the science doesn't work' (Ian, interview 05/08/16). Working with the PM Ian could see why the PM might wish to store a plate in the carousel while using the robot arm to complete a different process. However, Ian did not view the carousel as a storage facility in this way once he had filled the plates with live samples. It may have been inefficient to laboriously return a plate to the incubator each time the robot arms moved a plate between machines in the set-up. However, Ian recognised that by promoting growth in the samples throughout the steps in the process, by going back to the incubator repeatedly, this would ensure the results of the synthesis and analysis had the best chance of working as expected. Ian engineered the system with cellular behaviour in mind, whereas the PM's focus centred more on the robot behaviour and how to increase efficiencies in the length of time each process would take.

Here is it clear to see that the writing of a protocol is influenced by the orientation a user has to what counts as an efficient system. In Ian's account, the PM's idea of efficiency was all about the quick transit of objects around the system, but for Ian efficiency had to include an understanding of the living materials under his care. A plate full of dead samples was highly inefficient, no matter how quickly the plate transited through the system. I did not have the opportunity to interview the PM before he returned to North America, so it was difficult to gauge how much understanding the PM had of biological experimentation. For my purposes however, it was Ian's framing of his expertise as a different kind of engineering that stood out. Ian was positioning himself as a scientifically orientated engineer, and he used the example of the PM as an engineer 'through and through' (Ian, interview 05/08/16) to mark out this

difference. These boundary definitions formed part of Ian's identity as an amphibious researcher.

We can see that Ian's construction of an engineer 'through and through' may have multiple interpretations by examining Alex's views on what makes engineering in the biosciences different: '… I guess it is a matter of taste. Most of my friends are not really interested in … the biology thing … they just want to be engineers. But I really like the fact that it's with living stuff.' (Alex, interview 31/01/2017). For Alex, to focus on engineering biology is not the same as engineering a car. Engineering the 'biology thing' is to be an 'engineer plus…' it is an opportunity to work in an area that has not been saturated with engineering designs and processes, 'there is definitely space in this field, I think.' (Alex, interview 31/01/2017). In section 7.8 below I further unpack Alex's notion of space in synthetic biology. Briefly, I suggest that, for Alex, it is synthetic biology not automation that offers the most exciting frontier for imagining new kinds of research questions and application areas. In contrast, automation for Alex is about 'making synthetic biologists' lives easier.' Alex comes from a background working in software development in Silicon Valley and his account of himself is very much tied to finding technological solutions to others' problems. For Alex, synthetic biology will be the area that advances scientific understanding and helps to tackle global challenges. His job as a software engineer is simply to make that journey easier using engineering tools and approaches.

The way Alex describes his understanding of being an automation engineer in synthetic biology also contains a fascinating connection to pleasure. Alex is concerned with designing specific features in a system to help colleagues, and this makes him happy: 'Being an engineer makes you much happier. Because every day you work you make progress and [its] undisputable … You're just making new features and making other peoples' work easier.' (Alex, interview 31/01/2017). We can compare this to Ian's views of the PM. For Ian, the PM could not make the system work with the living cells in mind. Alex, on the other hand, recognised that making the system work involved making his colleagues' lives easier, and he had a sophisticated understanding of the different challenges facing engineers working with living things. Indeed, this

was the reason Alex chose to work in this field and he derived pleasure from making the AL system work for his colleagues and the living materials under their care.

I found Ian's and Alex's conceptions of engineering striking because they each positioned their own practice in contrast to other forms of engineering. For Alex, his friends were working on engineering projects in the car industry and elsewhere and he compared this kind of work to his own experiences engineering with biology. Alex described these choices as a matter of taste but it was obvious that he felt strongly about the exciting potential in the field of biological engineering. Alex became animated and spoke enthusiastically about the first time he read a paper by Craig Venter and realised that researchers could programme biology. However, for Alex automation is just a tool in synthetic biology, albeit an important tool that will make researcher's lives easier. Alex derived his pleasure from that process of solving researcher's problems rather than solving biological complexities using automation. In Ian's case, he expressed a strategic view of his interest in engineering. Ian seemed keen to make sure I understood that he was a scientist first and an engineer second. Part of Ian's strategy for achieving this aim was to construct a difference between himself and other system operators that knew only how to push "go" at the start of the day. Unlike Alex, Ian was keen to contribute to the scientific understanding of synthetic biology in a direct way.

Perhaps surprisingly, Ian was one of the most cautious advocates of automation at the AL. He was keen to stress that automation featured very little in his PhD, and that some tasks in the biosciences would become more automated while other tasks would not. Ian's sense of belonging was within the academic biosciences and it was my feeling that his long-term aspirations were not in-line with the AL's mission to become a service provision to other researchers. When I asked Ian about the future, for example, he indicated that he would be looking to move into research and development using automation in the pharmaceutical industry. Ian's version of an engineering identity did not seem as fluid as Alex's, and Ian did not seem to derive as much pleasure as Alex in using automation to solve others' problems. Ian's conception of systematic engineering was the same as he saw in the PM's approach to rational and efficient system design. Ian contrasted that framing of an engineer 'through and

through' to his own version of an engineering identity, a version that seeks to elevate understanding and create new knowledge of biology; Ian's interest in automation was usually secondary to that objective.

In the next section I look more closely at Alex's pleasurable engineering and how he and Ian worked together to design the AL system in ways that would eventually bring timesaving benefits for the AL team. Timesaving, as we have seen, was the first of five promissory narratives found in vendor and policy-maker descriptions of automation-driven synthetic biology. I go on to review each of the narratives in turn in the following sections.

7.7 Automation will result in more time for researchers (Narrative 1)

One of the key findings from my time at the AL was that setting up a large automation platform was a costly business. That the financial costs of any such large-scale system would be significant was not surprising. However, the incredible investments of *time* needed for planning, building and using such systems was not something for which my analysis of policy documents had prepared me. From Tilda's overview of the original procurement process, through Ian's descriptions of making the kit work, to Alex's account of making the teams' lives easier, time was the most significant issue that came up repeatedly during interviews. However, in contrast to the policy promises that automation would save researchers' time in the laboratory, all of my informants at the AL spoke of their difficulties with having enough time to meet competing demands. This section of the chapter explores some of those competing demands and argues that, as a new system researchers had yet to test through repeated practice, the AL platform's timesaving capacities remained latent. That is, timesaving remained a future promise for the system.

Furthermore, as the previous discussion illustrates, the timesaving capacities of the system in Ian's opinion were far from certain. Alex believed in the power of automation tools to make lives easier but, as I explore below, he was also aware of the need to remain 'agile' in their development. For Alex 'agile' development is about having the flexibility to respond to changing circumstances and priorities. How quickly the team could adapt to change was a measure of their system's efficiency for Alex.

This finding suggests that when it comes to the timesaving capacities of automation in the laboratory, the AL team rarely dealt in absolutes. It was hardly ever the case that Alex and Ian would devise one process, apply automation tools to that process and create a more efficient process. Daily, Ian would come to Alex with a list of things he would like to achieve with the system. Then, he and Alex would come up with programming scripts and try out those ideas on the system. Lots of the time, it was Ian's ideas about possible system demands in the future that drove their collective effort to automate, and those ideas were by their very nature speculative and without certainty.

Just getting a process to work was a considerable achievement and the team needed to get as many processes as possible tested before beginning to work on live customer projects. Perhaps in the future, as Alex makes clear below, the team would begin to look at all the working processes and try to ensure they were operating as well as they could. However, it would be difficult to attribute efficiency gains in these cases purely to the use of automation. Using the automated platform was often an explicit choice because several methods were available for completing each task. Ian and Alex particularly, were tasked with making the process of using the automated platform more efficient, which they could achieve with some difficulty as outlined below. However, the promissory narrative that automation in isolation provides efficiency gains for researchers was not borne out by my experiences talking to Ian and Alex at the AL. The system needed Alex and Ian to keep track of the system's capabilities and future efficiency gains would almost certainly rely on future users learning how those capabilities can be maintained, especially as research priorities and funder grant topics change over time.

Despite these challenges in realising efficiency gains through automation, Alex had ambitious plans for the role of automation at AL, particularly in helping their small team stay competitive in the DNA synthesis marketplace. During interview, Alex helped me to see one of the problems AL faced when compared to large commercial DNA synthesis services. AL were just not large enough:

> Here, really the name of the game is automating everything. Automation for everything because one reason is we're not that many [staff] so our competitors are like 50, 60 something like this, in [staff] teams. We are five and so everything we automate is something that frees the hands of [the laboratory manager and the automation engineer]. Or the operation team basically. (Alex, interview 31/01/2017)

When considering which elements of their daily work should be targeted for automation, Alex explains that he first thinks about the cost of different people's time and how much impact automation would have by 'freeing-up' that persons' time: '… how critical is the person that has to do it, because the thing is if … the modern apprentice can do it it's less critical than if [the laboratory manager] has to do it, because [the laboratory manager's] time is more valuable' (Alex, interview 31/01/2017). I went on to ask Alex for examples of how he might automate 'everything' and he clarified that he was talking about every task on the robot platform, but that even this was not straightforward. Alex needed to work closely with Ian and the team to develop scripts for the robots in response to changing needs, but also record and save scripts that they could use repeatedly. He called this 'agile development':

> We don't always know where we are going … So, I think they call it 'agile' development… So basically [the] first step is… day to day I write scripts mostly from scratch let's say. …When I have written a few of these I look for what is the most common, the biggest common part of all of this, and I package that part into a library. And then, so you get a library with the function that will present like a hundred lines of code but which you can call with parameters and so that you don't have to write it again every time you do it. But you have to identify this very, very carefully and you have to organise it very well because that will make how fast you can go in the future. (Alex, interview 31/01/2017)

The organisation of the different scripts was crucial. Alex was in a position to name the different parts in the functions library for the robot protocols, and he labelled these parts according to both how he was using them and how future researchers might use

them again. Alex was able to make these labelling decisions through his close working relationship with Ian. By working in this 'agile' way Alex viewed part of his role as keeping up with Ian and his many separate tasks and plans, writing new scripts for different ideas that Ian was trying out, and developing hundreds of protocols in the library that were designed with specific tasks in mind. However, eventually they had to sift through these many protocols so that Alex could begin to see common functions that they were using across the different range of tasks Ian had been completing in the past few weeks:

> So basically we try to have one or two weeks of storm and then if you like maybe one week of peace, where we can actually take the time to refactor. Because if you automate in pressure … and you never find the time to go back and look at what you do, all you do is accumulate bad code on bad code, what you call technical legacy or something like this. Basically you make it work but in the long term you know it will cost you. (Alex, interview 31/01/2017)

Alex and the team recognise that they cannot know in advance, which tasks they will need to write protocols for and they address this by writing many scripts for many tasks as Ian tries out different operations on the system. Ian chooses which tasks to test through a number of mechanisms, including liaising closely with Tilda and the management team to foresee in which kinds of projects the AL team will eventually get involved. Alex then takes time every few weeks to check through the code they have written, understand why it was written in a certain way, and decide if the code still works as intended, and with subsequent code they have written for other tasks. It is a combination of Ian's and Alex's working relationship, and knowing that how they design a script will create a 'technical legacy' for the system, that allows them to automate in ways that are 'agile' enough to be useful for their daily needs. This process of dialogue and adjustment requires both Ian and Alex to have an intimate understanding of the platform with which they are working, and an understanding of the living things with which their system is designed to work.

For example, Ian can look at a plate on the plate deck and see that certain wells may have marginally less liquid in than other wells on the plate. Ian knows that disparities

in sample sizes could affect his results and therefore understands that he may need to redo the plate. He also knows to check the liquid dispensing tips to make sure these tips contain filters that prevent cross-contamination between different wells. All of this Ian knows equally well if he is using a single barrel pipette and manually filling tubes. The difference he makes to the system is bringing that understanding to the automated platform and working with Alex to figure out how they can maintain their accepted good practice using a multi-channel automated liquid-handling robot. Maintaining this good practice using the robot platform takes considerable effort, expertise and resource, including time.

The timesaving potential for automation at the AL, then, is relative to the competence and expertise of Ian and Alex, and their ability to work together to create some common functions of what might be needed by platform operators in the future. During this initial set up phase, this testing and development was clearly the central focus of the work at AL. A dedicated postdoc with a multi-channel pipette could have completed many of the individual tasks they were trying to setup on the robot equally quickly. However, once these common functions of daily work on the platform were successfully operating, Ian and Alex were certain the robot platform offered researchers a way to complete certain tasks with far greater speed and efficiency. This is not to say that the AL robot platform would eventually replace the need for human operators altogether, especially when the task was a simple one for a human operator, but would take huge amounts of investment and development to complete using a robot:

> So imagine this. You have … a plastic plate with 96 wells and one of the things you have to do is empty the wells of liquid so, as a human all you have to do is turn the plate upside down in a sink and then all the liquid just flushes out. To get the robot to do it you basically have to pick up eight tips at a time and then, you know, suck up the liquid effectively and then bin it somewhere; you have to dispense of the waste liquid somewhere else. It's not the case that automatable solutions are always better than the manual solutions or are always faster. It simply isn't. Sometimes the automated solution is … so much slower and more expensive actually to implement than the manual process. It's the

> reason why pharmas don't tend to have fully automated systems because they factor the cost of the technician into the automation system. When you think about automation you tend to think about the hardware but actually a more sort of holistic view of it would be that you're going to have to need somebody to be around anyway. (Ian, interview 05/08/2016)

I would extend Ian's 'holistic view' to include his and Alex's input to the system, without which they could not keep the AL robot platform operational for the team's daily needs. Moreover, we can also take up Ian's invitation to see past the hardware when deciding if laboratory automation is going to save researchers' time. The seemingly mundane knowledge required to understand that a plate can be emptied in to a sink takes huge amounts of enculturation and learning to be carried off effortlessly. Human operators understand what a 'sink' looks like, where it is located, and how the pipes and porcelain work together to be suitable tools for waste disposal. A human operator knows how to understand different coloured stickers and signs next to each sink to designate that particular sink's correct use; is it 'hand wash only' for example. Ian and the automation specialists he admires recognise that automation will not replace the need for technicians because the investment required to replace a sink emptying process with a liquid handler waste disposal process would be enormous. It would not make business sense to even try. For Ian, to start talking about if this kind of replacement would be possible using robots and automation makes little sense, even if technically it would be more efficient in the long term to have a waste disposal step completed by the robot rather than a technician in the room to intervene each time a plate needs to be emptied of liquid into the nearest appropriate sink. The next section of the chapter looks in more detail at how the AL team decided when automation was an appropriate tool for a specific job. I use extracts from interviews with Tilda and Alex to understand their views on automation as a means to enhance the experimental space in biological research.

7.8 Automation will increase experimental space (Narrative 2)

As discussed above, the AL team were sceptical about the likelihood of full automation becoming the norm in synthetic biology. However, members of the team were committed to the view that their platform could complete some tasks that would be impossible without such a large high-throughput system. Similar to the RL team in the previous chapter, the AL team recognised that the robot platform could complete tasks that would be difficult for human operators to complete without access to robots and automation. During one interview, the laboratory manager Tilda describes an exchange she had with a researcher in a different laboratory. This researcher came to Tilda for help creating a DNA fragment that was only 100kb in length. For Tilda this is not what AL was for, and in her view, the researcher would have been better starting this first stage of work at his bench. Once he understood how this small fragment was behaving, acting like the wild-type DNA for example, then he could return to AL and ask for help modifying small things many times:

> [Once we] … know … what it [the small fragment] does, and it works like wild-type or whatever… [let's] see if I change this 100 times and this 1,000 times … what happens then in the cells. And that's where we come in because that will be easier for us [on the automated platform] … We only become useful when it's a big project. (Tilda, interview 28/07/2016)

However, for Tilda, an important consideration when using the robot platform, even for research taking place at the laboratory bench, was that this initial manual bench work was completed in collaboration with AL team. This is important because, in order to heavily modify small parts (e.g. 10%) of the DNA construct, the AL team would need to know how the collaborator had assembled the other 90% of the construct. This reflection demonstrates that, although the robot platform is not good at doing the initial small scale work, for the automation to be most useful later on researchers may find that they need to use the systems for things that human operators could just as easily do manually, perhaps could even do manually more quickly than the robot, at least for the initial finicky work of building small fragments. Researchers could then offset this initial struggle with the robot platform through later gains in running very large

numbers of variables and modifications, which is far easier if the robot platform has been utilised throughout the process.

I was particularly struck by Tilda's description of the value of the AL platform 'only becoming useful when it is a big project.' This was striking because in the same account Tilda also stressed that the large-scale modifications the platform could enable later on would only be possible through having knowledge of how researchers had put together the original small-scale fragment. The major promise that automation will enable an increase in the experimental space for biology hits a snag in these descriptions. It is not only the automation platform that enables the expansion. Rather, it is automated system operators having enough knowledge of the original design, perhaps through close collaboration with the designer, and the ability to make that design fit with the functionality of the high-throughput analysis tools. Seen in this light, the amphibious researchers at the AL enable that movement across scales and experimental methods. I therefore seek to amend Tilda's 'we only become useful when it's a big project' to 'the system only becomes useful when we can make big projects work.' In this way, amphibious researchers enable the expansion of experimental space by extending their epistemic infrastructure to make big projects work with high throughput tools.

The issue of experimental space did not only arise in relation to high-throughput technologies at the AL. As indicated above, Alex had his own reasons for choosing to move from software development in Silicon Valley to synthetic biology and automation in the UK. Alex talked about synthetic biology having 'space'; it was an area that was not saturated with automation application ideas. At first, I assumed that Alex was talking about using automation to further the ambitions of some synthetic biologists who sought to model the field on software engineering. I imagined that Alex's notion that synthetic biology had 'space' was coming from this idea of programmable biology with many untapped application opportunities. However, after subsequent conversations I understood that Alex was interested not only in the automated tools he could develop in the laboratory for the purposes of experimentation; he was also interested in developing automation for many aspects of a laboratory's routines. For example, he was responsible for developing a laboratory

information management system (LIMS) that could automate different aspects of the lab's routines, including automated stock ordering when supplies of consumables were running low.

On reflection, using automation for stock ordering and other rather mundane routines that keep a working laboratory functioning, was just as much a part of enhancing the epistemic infrastructure as high-throughput analysis tools. For Alex, there was 'space' for automation in the field of synthetic biology similarly to other industries such as car manufacturers. The space that was now occupied by software engineers in car manufacturing for streamlining and standardisation production processes, for Alex, was still open in synthetic biology. This streamlining and standardisation applied to the processes and routines of the laboratory workers as well as the cell samples with which they worked. Despite Alex working for a DNA synthesis centre selling full automation to a yet to be determined customer base, Alex seemed to belong among the groups outlined in the second part of Chapter 4. Similar to Charles Fracchia and Eric Klavins, Alex viewed software engineering as the solution to problems in the biosciences, rather than the enabling of full platform hardware of a robotic assembly line and connected laboratory experimental infrastructure. For Alex, automation could improve processes including stock management and machine maintenance schedules and, I argue, if and when the AL team makes these improvements, they should be counted alongside the contribution of automation to the expansion of experimental space in synthetic biology. In either case, whether automation is high-throughput or mundane process improvements it is the operators and system designers that facilitate and agree upon the inclusion of new tools and methods as part of their epistemic infrastructures.

In the next section, I further examine promises of improvement for the biosciences using automation by focusing on the claim that automation increases the reproducibility of experiments.

7.9 Automation will result in more reproducible experiments (Narrative 3)

As Chapter 4 outlined, a major benefit that system vendors propose for using automated platforms is that automation standardises the way biosciences experiments are completed. As pipetting is the primary mechanism for conducting an experiment, having a standard way to pipette different mixtures and solutions should promote the ability to reproduce that same mixture at a different time or place: that is, to make the experiment reproducible. However, having standard kits for pipetting is not unique to automation. Indeed, as Alex explains '…most of the pipetting we do corresponds to protocols which are clearly established and they come with the kits, basically. And it looks like an Ikea kit; it has little drawings and explanations.' (Alex, Interview 31/01/2017). So what is it about automation that will further promote reproducibility of pipetting techniques?

For Alex, this is not a simple case of transferring Ikea-like instructions to the robot platform, and thereby cutting out the assumed human error that causes different researchers to make up the same mixtures and solutions in different ways. The key for success on AL platform is that users have an ability to troubleshoot and understand when a process or result has not gone as planned; it is a case of saying… "[Okay] it didn't work, so why didn't it work?" …[Y]ou have to put a hypothesis based on your past experiences, that's where experience as a biologist comes in (Alex, Interview 31/01/2017). The automation engineer Ian agrees, and goes on to explain that human intuition for when a researcher has completed the pipetting correctly is still a major part of using an automated platform:

> '…sometimes if there's even slight variations in, for example, the liquid level a human can say "oh that one's got … a bit less liquid so I should add a little bit", top it up a little bit more or whatever. Good luck trying to get the robot to do that because the robot usually has no idea. It treats all 96 samples in exactly the same way. If that one doesn't have enough liquid then it doesn't know, it doesn't care. So that little bit of intuition which a technician could apply, the robot lacks. (Ian, Interview 05/08/2016)

Furthermore, Ian is sceptical of a new wave of robots with sensory capabilities that can 'see' with cameras, and make the kinds of intuitive judgements of a technician outlined above:

> I mean you can get a lot of these robots now with cameras and infrared sensors and you think god that will be the solution to it all but no, it really isn't because yes, the camera can give you more sensory information but it's very, very far away from the amount of AI you would need to say oh there's a little bit less liquid in that one so I should top it up a little bit more. It's not that straightforward. (Ian, interview 05/08/2016)

The automation systems like AL platform do not, by themselves, increase reproducibility. There are judgements to make during every operation, on any system about the correctness of the robot techniques, even when following a standard 'Ikea-like' set of instructions. As my experiences of completing the system demonstration at the RL (Chapter 6) demonstrate, instructions can be standardised but often operators and environments cannot. Like all biosciences work the experiments and processes hit obstacles and do not proceed as planned, and this is true of both automated and manual methods, albeit with different kinds of attentiveness required to overcome these problems and get a desired result. As with the account above of collaborations between Alex and Ian, creating common functional parts that researchers could use to complete a task repeatedly on a robot platform was not easy. Indeed, even the same researcher using the same platform over time makes tweaks and adjustments to keep his/her processes and results within accepted limits. The standardisation of data outputs, that is, the format in which data is presented could be one area that automation contributes to in terms of reproducibility. However, all my evidence points to the essential ingredient – an amphibious researcher – to generate good results from an automated system. Moreover, it is the standardisation of researchers' practices that has the greater potential for reproducibility rather than the compete automation of all tasks using liquid-handlers and robotic arms.

7.10 Automation will increase technological capacities (Narrative 4)

Ian's comments about the limitations of robots for doing intuitive work helps to problematise one of the big claims that *Biodesign report* authors make for capital investments in facilities like AL. I phrase this claim as follows: large-scale automation facilities boost the technological capacity of research institutes and create a competitive advantage for their institutions, which in turn progresses science and furthers the policy agenda for biosciences research at a national level. These claims, as I argued in Chapter 4, are implicitly technologically determinist. That is, they do not recognise the agency of system-users and policymakers to shape the direction of technological development.

For the AL team it is clear that, despite having committed to designing a fully automated platform for creating very large DNA fragments, in practice full automation is unlikely to be achievable. Moreover, full automation does not make financial sense: 'I would say in 99% of cases, it's cheaper and better to just get a human to do some of the steps.' (Ian, Interview 05/08/16). Perhaps most importantly, there are so many different types of tasks associated with completing a successful experiment or building even simple fragments of DNA. A robot could perform some of these tasks but the effort required to do so is so great that no sensible system builder would spend time automating everything:

> Where are you going to stash all of these things, right? You're going to have to stash them in a special carousel so that the robot can pick them up because they have to be precisely positioned, whereas for a human, I mean, just dump the cardboard box in a drawer, they will go find the box and the containers inside and you don't have to stash them in any particular order, you know. If they can read the label, they can find the containers. […] A trained monkey could do it. (Ian, Interview 05/08/16)

Despite Ian's assertion that a 'trained monkey' could replace consumables on the automated platform, even a highly sophisticated robot arm would struggle to do so. Investments in automated platforms, and understanding what is required to keep them working, needs more thought than just the technological capabilities of the system

itself. There are questions about how to design the system so that a so-called trained monkey can use it safely, and how such a cohort of monkeys might achieve the right level of training in the first place. As shown in the RL chapter, training is part of learning how to be in the world of people and things. An 'attentive engagement' with robot platforms in the biosciences involves knowing both people and things. It is learning how to be the right person, and making the right judgements that result in the right experimental results. This is all shaped by, and helps to shape, the artefacts humans create, and our relationships with one another. In my view then, Ian's trained monkey analogy does not give appropriate credit to the complex social relationships any operator negotiates to keep a robot platform functioning in the biosciences. Like Rosalyn in the previous chapter, Ian does himself a disservice by glossing over the abilities he and other operators have to deal with the messiness of a functioning system.

In the next section, I turn to the final policy narrative extracted from policy documents on automation and synthetic biology that linking up these two areas will result in further commercialisation opportunities in these fields.

7.11 Automation will enable further opportunities for commercialisation (Narrative 5)

When I asked Ian about his future career plans he focused on the value he had built up by developing a system 'from the ground up' (Ian, Interview 05/08/2016). He explained that large commercial businesses worldwide deployed these kinds of automated laboratory systems, and that is definitely the direction he '…would be heading towards in a few years' time.' (Ian, Interview 05/08/2016). Ian's particular skills, his 'attentive engagement' with AL system was how he imagined himself to be set apart from a technician or operator that worked with a system on a less involved level than he has done with this platform:

> So there are people who run automation systems whose job basically is to press go at the start of the day. If it breaks down they reach for the phone and call out the service engineer and then they refill the consumables. … That's not what I've been doing [here]. So when I think about my future career trajectory

> [it] would be towards the applications side because there I have the advantage. I can make the science work with the automation. (Ian, Interview 05/08/2016)

My experiences observing Rosalyn at the RL case study site caused me to reflect on Ian's proposed scale of technical competence. Reflecting on this later I wondered whether Rosalyn was as involved as Ian was with writing programming code 'from the ground up' to get EMA set up. This seemed unlikely considering that Rosalyn inherited a system that was designed by different users for different purposes many years previously. However, to suggest Rosalyn merely pressed 'go' at the start of the day seemed inaccurate also. In the end, I am unconvinced that any system can run simply by pressing 'go' at the start of the day. My own interpretation is that pressing 'go' is too binary for imagining how an automated system is made to function, and has connotations that the system can either be on or off, running or not running.

However, for an automated system in the biosciences a running system is one that is functioning in the right way. This insight builds on claims made throughout this thesis about problematic dichotomies. Boundaries between science and engineering, or between real and not real robotics (e.g. Peter's interview in Chapter 5), are rhetorical games of inclusion and exclusion. Experienced operators make judgements continually, depending on whether the outputs of the system look and feel right and if they conform to the expectations the users have of this particular system at this time. In this way, proper functioning is a precarious achievement, and even relatively junior technical operators perform tasks, however seemingly mundane like filling up consumables or emptying a waste bin, that contribute to this assessment of proper functioning. It seems that successes made through automation are relative to complex and precarious user judgement about proper functioning, and boundary-work is one way that system users deal with this precariousness.

All of this leads me to reflect on the promissory narrative that automation for the biosciences will lead to increased commercialisation opportunities. The primary policy narrative is one in which increasing automation facilities will create more efficient and productive laboratories which in turn will generate new business opportunities in the form of synthetic biology products: scents, flavours, drugs and other valuable

compounds. However, this is too simplistic for understanding the purpose of the automation system at AL. The AL team may well be aiming to help researchers build large DNA fragments, and those researchers may then derive new insights into cellular mechanisms that will one day result in a tangible business opportunity to create a consumer product using an automated facility. However, the immediate commercialisation opportunities for AL team are in some ways far more modest.

The AL team is hoping to create a fee-charging service for other researchers to use. Tilda, Alex and Ian want to use their expertise and the robot platform for assisting in DNA design, production and analysis. However, this ambition is also precarious because these kinds of services already exist on a commercial scale so AL must offer something different. Alex explains how AL can compete with large commercial competitors:

> '…where we can get customers is for people who have non-conventional or exotic projects. Because these projects cannot really be fulfilled by Twist or Transcriptic …[O]ur segment is more to accompany scientific projects while providing actual expertise which big companies may not have the time to do. (Alex, Interview 31/01/2017)

However, one way to offer those services, through a customer interface, would take many more developers than the three the team currently have. Therefore, to focus heavily on generating a sleek customer facing business online, so that potential customers could design and order their DNA fragments quickly and easily, would mean the team would need to shift their focus away from the development of the core robotic set-up: 'So that's a choice we have to make.' (Alex, interview 31/01/2017)

Another choice affected by the opening of AL facility is how any fee-charging services they offer will affect existing laboratory automation facilities at the university, operating similar services. I visited one such facility at the institute in which AL is based and interviewed the main operator of the liquid-handling robot there. The operator was relaxed about the opening of AL but spending time with her did help me to see that this idea of creating centralised laboratory services for DNA synthesis and analysis was not new. It seemed that the initial AL ambitions for commercialisation

were that it would become a specialised large fragment DNA synthesis company that would attract customers and collaborators globally and become a self-sustaining business unit in time. Perhaps this goal is still achievable as the AL is still in its formative stages. However, this more localised business model of offering ad-hoc automated services to researchers in their own institute could well be an acceptable second prize, even if it means that '… maybe some of the smaller facilities will have to go… this is a decision the university needs to make' (Tilda, Interview 31/01/2017).

7.12 Conclusion

In this chapter, I have used observations and interviews at AL to show how its aims are multiple and at times contradictory. The AL manager has the clearest vision for AL as a technical facility for the provision of DNA synthesis and automation tasks for other researchers. However, even Tilda's narratives about the directions of the AL, where it has come from and its imagined future, do not exactly align with this vision. Her description of developing new methods and being part of a collaborative process, even as outside researchers pay for their services, suggests that the line between technical service provision and academic research contribution is far from fixed.

The reflections of the software manager and automation engineer offered the clearest insight into how the potential for automation in the biosciences depends largely on what one is trying to achieve. For Alex, the software manager, AL is part of the emerging synthetic biology community and will provide more specialised DNA synthesis services than the large DNA synthesis companies based in the US and China. AL has the ability to tailor its approach to research projects with complicated and unusual DNA synthesis and analysis requirements. It is this ability to be agile and to reduce technical legacies in their systems that Alex believes makes AL a relevant player in the synthetic biology market place. However, even Alex concedes that AL cannot focus on developing front-end customer service and customer interface tools because it does not have the resources to be a competitive business unit that competes with large DNA synthesis companies with huge developer teams and marketing

budgets. Therefore, the customers for AL will be mainly derived from the ongoing (and established) funding streams attached to major research projects.

Ian the automation engineer's imagined future for AL is one in which full automation is not merely a near impossible goal, it makes little sense to even attempt to achieve it. His unique experience working with both the behaviour of cells and the behaviour of robots means that Ian feels his identity as an automation engineer in the biosciences is something more than a system operator who pushes 'go' at the start of each day. For Ian, this system building knowledge, which I am calling amphibious working knowledge, will serve his future career ambitions well as he plans to take up system development roles in pharmaceutical and biotechnology commercial businesses. A major part of Ian's self-understanding as a competent researcher with valuable skills was his commitment to highlighting the scientific value of the work he has completed at the AL. In contrast, Alex created a sense of belonging among enthusiastic problem solvers with software engineering as their major tool. For Tilda, her commitment to delivering a serious and orderly service provision seemed to be part of her alignment with the business-like objectives for the AL's senior leadership. However, Ian, Alex and Tilda had shifting allegiances and commitments and they responded to a set of competing demands. These amphibious researchers had to lead double lives to justify their past choices to design a fully automated robot platform, their current commitments to certain ways of organising workflows, and their future speculations about career choices and the financial viability of the AL as a service provision.

CHAPTER 8:

Amphibious researchers and the reconfiguration of promises: synthesis and conclusions.

8.1 Introduction

The origin of the word amphibious is the Greek 'amphíbios,' which translates literally as 'living a double life.' Breaking this down further, amphi- means 'of both kinds' and bios translates as 'life.' What does it mean for a researcher to be 'of both kinds of life' in automation-driven synthetic biology? My concluding chapter offers some insights and brings together the various lines of enquiry developed throughout the thesis. After outlining the aims and structure for the chapter, I present findings based on the five promissory narratives I identified in Chapter 1. Briefly, these findings show that the lived experiences of automation-driven synthetic biology reconfigured the five promissory narratives. Part of that reconfiguration was laboratory users' attentiveness to both cell behaviour and robot behaviour, and how such attentive engagement formed part of laboratory users' conceptions of who they were and their sense of group belonging. Moreover, as the final parts of this chapter outline, automation users developed their attentiveness to their tools and their cells through cultivation of a 'fingertip-feeling' (MacKenzie 1999) for cells and particular robot systems. In these ways, automation users in my study were amphibious and needed to be 'of both kinds of life' to sustain their understanding and to keep their systems functional.

It is important to note that my research journey and the observations I have made were not always orderly. The meaning of particular episodes in the empirical work did not shine through until many months after I had completed the ethnographies and interviews. Over the two-year empirical phase of the project, I was able to reflect upon earlier findings through the lens of later insights. The conclusion of this process was dictated by the funding and time constraints of a PhD programme. It is because of the multifaceted and, at times, contradictory character of my findings that facet methodology was so useful for my work. As we have seen in Chapter 3, facet methodology (Mason 2011) holds that a research object, in my case automation driven synthetic biology, is understood most fully when light is shone upon it from different

angles, and by using different methods. In investigating seemingly disparate facets of my research object I allowed those different planes and surfaces to cast strategically illuminating patterns; often by reflecting on very small moments I was able to gain greater understanding.

For example, I 'played' at being a system demonstrator: I put on my white coat, performed a system demonstration, and gave an interview to a visiting science journalist. To be convincing enough as an amphibious researcher I needed direction from a true amphibian, Rosalyn at the RL. The moment came when, even while hundreds of miles away, Rosalyn talked to me and directed my movements to bring the system back to life. I experienced a strange ambivalence: at once a successful operator under observation, but at the same time a charlatan, an impostor, grasping clumsily at a system that I could operate in a sense, but a system that I could not make functional. As Rosalyn instructed me to feel the plastic cover, feel the wobble, and feel it click in to place, I knew that I was feeling these things, but not quite amphibiously. I needed more time with Rosalyn, the RL team, and close working with that particular system to truly develop Rosalyn's levels of 'fingerspitzengefuhl,' her embodied fingertip-feeling (Mackenzie 1999). My ambivalence and non-belonging helped me understand that for Rosalyn, the RL team, and in later interviews at the AL, this embodied fingertip-feeling was part of those researchers' identities.

8.2 Aims of the chapter

One of the aims of this chapter is to take forward issues addressed in the previous chapter: researchers developing automation systems for biosciences research must manage competing demands. Some of those demands are unexceptional for most academic researchers in the biosciences, including the struggles of PIs to deliver ambitious promises made in funding proposals once the grant is funded and the complexities of the work become clear. However, for researchers at the AL these demands also included planning and acting as a customer-facing service provision, at the same time as demonstrating the centre's value within an academic enterprise. For example, the AL originated from within an academic laboratory and continued to target potential users interested in collaborative research. At the same time, the AL was attempting to create a brand new business model that separated existing notions

of collaboration, and created in their place a customer-supplier relationship. In order to build the AL system and generate interest from other researchers, investors and commercial partners, the AL team had to live double lives and negotiate these existing and new relationships simultaneously.

The second major insight about automation-driven synthetic biology is that, to be successful, system users need an understanding of robot behaviour, and an understanding of cell behaviour. It is important that a successful system user develops these understandings. However, having knowledge of computer programming and cell biology is not sufficient to maintain system functioning over time. Amphibious researchers also need to develop and *sustain* these understandings through membership of different knowledge communities in biology and software engineering. By teaching and learning from other community members, system users develop an intuitive and embodied 'fingertip-feeling' for how to maintain correct functioning. It is through this teaching and learning that researchers generate trust in their systems, and confidence in their results. Furthermore, it is this combination of embodied knowledge, training, and agreement about good and bad results that constitutes the practice of amphibious working knowledge.

The development of an automation system in the biosciences involves more than considering which tools to buy: system development is as much about knowing how tools can be adapted and made to work for specific users and their changing needs and career ambitions over time. By focusing on the importance of amphibious researchers for developing successful and functioning systems in the biosciences, this thesis contributes to understanding in the field of the social shaping of technology. By demonstrating the crucial role of amphibious researchers in automation-driven synthetic biology, I emphasise that technology is bound up with people in the same way that people are bound up with technology: each shapes the other. My analysis of identity and skills, that is, how attentive engagement (Ingold 1997) and passionate attachments (Butler 1997, Petersen 2007, Petersen 2013) to tools and methods contribute to group belonging and user identity, further underlines how people are bound up with and shaped by technology (Pinch and Bijker 1984, Mackay and Gillespie 1992, Williams and Edge 1996, MacKenzie and Wajcman 1999, Wajcman

2006). Once we can see the mutual shaping of people and technology more clearly, in this case automation-driven synthetic biology, the potential for intervening and directing the paths that technology takes is amplified.

8.3 Structure of the chapter

In the following section, I take the five policy and vendor promissory narratives detailed in Chapter 4, delivering findings on how the lived experiences of laboratory users challenged and reconfigured them. Part of that reconfiguration relates to choosing the right method for experimental work and judging when results are good enough. Here again questions of method are shown also to be questions of identity. Furthermore, as already detailed, keeping a system functioning to create good enough results requires an embodied fingertip-feeling for each particular system and groups of users and collaborators. The final two sections of the chapter unpack these notions of identity and embodied knowledge in more detail. The conclusion presents some overarching themes and suggests possible areas for future research.

My aim in the rest of this chapter is to explain how a number of facets in my research provided the 'flashes of insight' (Mason 2011) that opened up avenues of understanding for the rest of the work. One important ethnographic moment (Strathern 1999) in the study, was my experience in the audience at the industry-academia workshop outlined in Chapter 5. As I sat and listened to a series of speakers promoting ever more sophisticated automation tools, including silicone chips replacing microtiter plates, and laboratory automation representing a new paradigm in biosciences research, Kieran, the PI at the RL stood up to give his presentation. Kieran was a vehement proponent of the necessity of computer science for solving the problem of biological complexity. In many ways, he could have fitted neatly in with the rest of the speakers and hailed automation as a new paradigm in biosciences research, but he did not. Kieran warned against a 'balkanisation' of automation tools. He made this warning not because he did not believe in the power of computer science and laboratory automation – his work was well established and world leading in this area – he made this warning because he could see new and powerful businesses entering a space he had occupied for some time.

For Kieran, talk of a new paradigm did not fit with his own laboratory's narrative of continuity. That is, talk of a new paradigm interfered with his laboratory's story of progression from humble beginnings, failed journal article and funding proposal submissions, to successful proof of concept research and large international grant collaborations. For Kieran and the RL team the content of the workshop was no more a new paradigm for them than their own research practices would represent a new paradigm for the industrial biotechnology companies attending the workshop, whose focus was industrial-scale production of compounds of value.

By reflecting on this episode much later, I understood that the policy promises about the future value of automation (Van Lente 1993, Michael 2000, Frow and Calvert 2013b) only legitimised *certain kinds* of actions in the present. The visions in the policy accounts in Chapter 4 did not legitimate the RL's actions because their particular form of automation was not sufficiently in line with the policymakers' ideas of the 'bioeconomy.' Kieran made predictions about the future value of the RL systems many years previously and those promises related to using robots and machine-learning for producing novel scientific knowledge. The RL's 'proof of concept' in this area is what provided the sustained interest and funding for their system. However, these predictions and proofs of concept became legacies of an older system and the RL team had to adapt its focus to different funding body interests and forge new collaborations; none of those collaborations involved the newer wave of synthetic biologists. This insight strongly emphasised the importance of understanding the lived experiences of different kinds of laboratory users trying to develop automated tools. Not only do promises of future value legitimise some kinds of actions and not others, separate and different promises about the same technologies can coexist and do not need to be in direct competition. However, understanding different lived experiences of using and developing those technologies shows the unpredictable effects of policy promises, and that users can and do reconfigure those promises to meet their specific needs and goals.

8.4 Strengths and limitations of the research

It is extremely hard to predict how far promises about automation will eventually come to shape the future of the biosciences. There are multiple possible futures in

automation-driven synthetic biology, as the previous section and chapters have highlighted. Perhaps because of this open-endedness it is important to remain sensitive to the contingencies of my findings and the historical context in which the research was conducted. For example, ambiguity about the importance of automation for the future of synthetic biology was a salient feature of the study. However, it is necessary to bear in mind that the duration of time I could spend in the field, observing the case study sites, was also constrained by the formal requirements of a PhD programme. I had just over two years from the beginnings of the pilot work to the last of the follow up interviews to track the changes at my sites and to begin synthesising my conclusions from those observations. These time limitations meant that some of my actors' claims about what automation will eventually enable in the medium term could not be evaluated in practice. Moreover, because those claims were not homogenous and often needed to be grounded in the context of specific users' aims and expectations, it was a challenge during my limited research window to speak about changes to automation in the biosciences more broadly.

I have outlined some of my strategies for tackling this challenge throughout the thesis, particularly in Chapter 3. I selected facet methodology as my starting point because I could see the value in connecting several moments of revelation picked out from many hours of talking to and listening to my informants and their day-to-day cares and aspirations. Moreover, it was witnessing and sharing in these multiple lived experiences that provided the critical data for my empirical chapters. My detailed descriptions and longer-term relationships with my informants allowed me to witness the importance, not just of the automation tools, but of the communities and identities that formed around and shaped these tools in the pursuit of proper functioning systems. It was the tensions and resistances I observed in getting systems to work for different users' needs that provided crucial data points in my study. These tensions helped me to see that, without a deep connection to their particular tools, and to the workings of the cells handled by those tools, researchers at each of my sites would have struggled to feel connected to a meaningful research programme that could be shared with their fellow researchers. Moreover, without this community of amphibious researchers my

informants would have struggled to imagine a future that would make their many set-backs and failed experiments worth such considerable effort.

It is conceivable to imagine a world in which these considerable efforts in the short to medium term will lead to a routinisation of automation in the biosciences; my informants could be early pioneers in this regard. Moreover, my fortuity in gaining access to these researchers and sites so early on in their use of automation tools, especially the Assemblers Lab, may well lead to over-emphasising the fragility of automation because its power for the biosciences is still far from stabilised. This was one motivation, as discussed in section 3.4, for choosing the Rhodes Lab alongside the Assemblers Lab as a case study site. The Rhodes Lab has for more than a decade been championing many of the liquid-handling tools now purchased by the Assemblers Lab. So what is it about this particular moment that foregrounds interest in automation as an underpinning technology for the biosciences, and what factors are influencing this trajectory that were not present ten years ago? I have identified specific policy initiatives linked to robotics, automation, and synthetic biology (see Chapter 4) that explain some of the renewed focus on capital investments in this area. However, in addition to promoting the power of automation, these same policy initiatives recognise the uncertainty of the need for large-scale automation in the biosciences (SBLC 2016).

In Chapter 4 I also highlighted more recent forms of automation in synthetic biology that do not utilise liquid-handling robotics in any significant way, such as the use of motion-tracking and smart lab technologies. Ultimately, as articulated above, making predictions about which form of automation might transform the biosciences or otherwise is difficult and in the end, not particularly useful for understanding how current configurations of systems, skillsets and research priorities are organised and made to work for specific aims, particularly in synthetic biology. Moreover, the future of synthetic biology is still uncertain and it is widely recognised as a field still in the making (Calvert and Martin 2009, Molyneux-Hodgson and Meyer 2009, Kronberger 2012, Schyfter and Calvert 2015).

However, understanding the present to explore some of the many possible futures in automation-driven synthetic biology does form part of my ambition for the usefulness

of this research. Arguably, these ambitions can only be partially met during the lifecycle of a PhD project. To better understand how truly radical or transformative automation may be for bioscience researchers, and the extent to which these tools will become part of an invisible taken-for-granted infrastructure in the life sciences, additional and longer term studies are needed. To this end, my postdoctoral plans include further longer term research with a large automated DNA synthesis centre closely aligned with the Assemblers Lab. This linked centre has a mature automation platform and funding to work closely with industry partners on various scale-up projects to create commercially viable compounds of value using synthetic biology techniques. It will be fascinating to explore what, if any, is the role of amphibious researchers at this centre. During the next phase in my career I will consider to what extent the skill-sets I have observed to date are disappearing into the routine infrastructure of a commercially focused enterprise in automation-driven synthetic biology.

8.5 Challenging promissory narratives of automation-driven synthetic biology

The technical capacities of machines only really become clear during use. In the next five sub-sections, I present my findings in relation to RQ1: In what ways do the lived experiences of laboratory users support or challenge the promissory narratives of laboratory automation for the biosciences? My findings demonstrate how the lived experiences of laboratory users reconfigured the policy promises around automation-driven synthetic biology.

8.5.1 Findings for Narrative 1

Policy and vendor promissory narrative: *Automation will result in more **time** for researchers because robots are more efficient and more accurate, especially for repetitive tasks.*

The lived experiences of laboratory users in my study challenge policy narratives about the timesaving capacities of automation-driven biosciences research. Timesaving using automation was relative to the kinds of tasks users in my study wished to undertake. For example, when informants at the RL used the robot platform to conduct

continuous yeast growth measurement over 42 hours, the system repeated the same cycle of measurement and incubation every 20 minutes. The RL team used the robot arm to move its plates between the optical density plate reader and the incubator. The plate reader measured how many cells had grown every 20 minutes and this data enabled the RL team to plot the growth curves of different yeast samples. However, I had to weigh the time saved as the robots completed this process overnight or during weekends against the effort required to set up this measurement-incubation process, especially if the RL team needed to make any changes to the process. This is the crucial insight about the time saving potential of automation in the laboratory: even highly repetitive tasks need to be adapted according to user needs. The RL team needed to intervene in the measurement-incubation process and introduce a lid-lift protocol because the team believed the samples needed more oxygen between measurements. Therefore, the timesaving capacity of laboratory automation remains promissory in many areas of biosciences experimentation, unless the task that needs completing is highly repetitive and unlikely to require ongoing adjustment.

8.5.2 Findings for Narrative 2

Policy and vendor promissory narrative: *Automation will enable greater **experimental space** by increasing the number of parameters that can be tested in parallel, and the ability to tackle problems with very large numbers of variables.*

The policy narratives around automation and the expansion of experimental space posit that a combination of machine-learning and laboratory robotics represent a new paradigm in research capabilities in the biosciences. In Chapters 4 and 5, I explored this notion of a new paradigm and concluded that many vendors offer high-throughput laboratory automation services, but the take-up and distribution of these tools is still very uneven. Furthermore, my experiences at the RL discussed above demonstrate that linking automation and experimental space with a new paradigm in biosciences research is a rhetorical move.

I have found some agreement among my informants that laboratory automation, robotics, liquid-handling, and machine-learning do have a place in some areas of experimental research. A different framing of the expansion of experimental space

might therefore be applicable in the case of automation in the biosciences. If I conceptualise experimental space as the abstract idea that tools buttress understanding in scientific practice then I can also see how automation offers an expansion in the epistemic infrastructure of the biosciences. Some practitioners now agree that automation and liquid-handling robots can produce good experimental results. Arguably then, it is those users' collective agreement about acceptable methods that results in an expansion of experimental space, because more tools are available for making that journey to collective understanding. However, automation tools, like collective understanding, are fragile and difficult to maintain without investment and support over time.

8.5.3 Findings for Narrative 3

Policy and vendor promissory narrative: *Automation will enhance the* ***reproducibility of experimental results*** *by breaking down experiments into repeatable steps and standardised protocols.*

Automation in isolation does *not* create more reproducible results. In almost all areas of my study, I could not break experiments down into easily recordable steps. When the AL team first envisioned its system as a fully automated platform, it was understood that full automation of all the steps was not only unlikely, but undesirable too. The reason Ian and the AL team baulked at full automation was that many other industries, including large pharmaceutical companies, had been using large automation platforms for years and did not attempt full automation. In interviews with Ian and the AL team, the reason for not automating certain tasks, including emptying the waste from a used plate, came down to time and cost implications. It was cheaper and more effective to employ a technician to continue to do some of that work. However, a further reason for needing technicians and other operators around is that they build up expertise on the idiosyncrasies of each individual system. My data shows clearly that all systems have idiosyncrasies, not least because no two systems are ever dealing with exactly the same set of problems, employing exactly the same researchers, or operating at exactly the same moment in time or physical location. All of these factors influence even the most standardised process. If, as Chapter 5 described, humans cannot be standardised, and automated systems in the biosciences cannot function without

humans and their amphibious working knowledge, then full automation and universal standardisation are not achievable ambitions.

8.5.4 Findings for Narrative 4

Policy and vendor promissory narrative: *Automation will increase **technological capacity** making laboratories more competitive in the international funding arena.*

The idea that research institutions would become more competitive through increased funding in capital infrastructure, automation platforms, and synthetic biology was a promissory narrative found in policy and vendor documents (see Chapter 4). This promissory narrative was difficult to track in any meaningful way during my empirical work. I found that the high levels of activity in developing automation platforms for synthetic biology were still drawing from their original funding schemes. The AL team did express anxiety around what would happen when these funding schemes ended, and showed some reticence that the AL could generate enough income as a service provision to fill that gap. Given that the AL team continued to cultivate relationships and collaborations with academic researchers based in their institute, future collaborative proposals that state a requirement for automation tools in their research seem likely. It was too early to make any real headway in this area for the AL. In contrast, the RL team was ten years in to its system usage and the PI, Kieran, had traversed several university posts, systems designs, and funding body support to keep the system active over this period. That the RL team continued to attract international funding after the original grants expired might suggest that automation increased the competitiveness of the RL for funding rounds. As Chapter 6 explains, however, these battles for funding were hard-won by Kieran and the team and, I argue, any continued success based on automation for the RL is a result of that collective effort to adapt the focus of the system according to changing funder requirements.

8.5.5 Findings for Narrative 5

Policy and vendor promissory narrative: *Automation will provide further **opportunities for commercialisation of products and services**, either directly by using automation to build DNA, or indirectly by creating research economies based on consumables and service plans.*

One of the central policy promises is that automation-driven synthetic biology will fuel a burgeoning bioeconomy. The typical narrative posits that automation increases productivity, and by increasing the speed that researchers can manipulate biology, automation will help feed an innovation pipeline. Researchers' increasing use of automation will then further boost this pipeline and this will increase the ability to scale-up the industrial production processes required to manufacture compounds of value using synthetic biology techniques. However, a major problem with this narrative is that automation in isolation does not speed up understanding of biological complexity. There are a number of companies using automation in industrial scale synthetic biology productions processes, including the example of artemisinin production provided in Chapter 5. My research focused on the academic biosciences in the UK, however, and there was a significant disconnect between the interests of those larger industrial companies and most of the academic laboratory leaders I met during the study. As noted in Chapter 5, even strong advocates of the new paradigm approach recognised a need to deploy smaller desktop liquid-handlers to other laboratories in their institute. Large-scale commercial scale-up operations did not form a large part of UK academic interests, and therefore using automation directly to produce new products for the marketplace remains a promissory narrative. A future study of automation use in large-scale industrial synthetic biology companies would help further understanding in this area.

However, there are other commercial consequences of laboratory automation. For example, partnerships between commercial technology vendors and universities have increased to meet the demands of the capital infrastructure investments outlined previously. When universities procure new large equipment, they often purchase the equipment and, in the AL's case, pay a company to integrate the different machines in the system. By stipulating that universities could only purchase capital equipment, funding bodies committed universities to use part of their budget and income to pay commercial vendors' salaries and contribute to their profits. This is a form of commercialisation because universities enter into partnerships that create business opportunities, albeit with profits entering the private sector rather than funding further research.

A further extension is the service contracts that both the RL and the AL continued to pay for after purchasing its equipment. Often vendors produce bespoke systems or controlling software and those purchasing a system are tied into using the company to maintain the parts of the system over time. The discussion between Tilda, Ian and an engineer from a vendor in Chapter 7 was a good example of the complexities in these service arrangements. For the RL, after ten years of use, service contracts and system changes were so prohibitively expensive that users had to make choices about which problems they could address and those problems they would have to live with. For example, getting a machine serviced while an engineer came to make a small repair made sense for the RL team. However, upgrading the entire platform from Windows XP had such potentially astronomical costs that the RL team would not risk it. Again, in the example of service contracts we see that a commercial partnership has been set up and maintained but the continued financial benefits to the research institute are less tangible than for the vendors providing the contract.

Finally, automation platforms require consumables, including plates, pipette tips, and grippers. Again, the experience at both the RL and the AL was that marketing of consumables was big business, and the teams at both sites often spent time fielding calls and visits from consumables supplier representatives. Tilda even joked at the AL that she needed a full-time person to deal with sales calls. Furthermore, consumables can be machine-specific. For example, one acoustic dispensing liquid-handler supplier stipulates that users can only purchase their own brand plates for use on the machine, which Rosalyn (interview 11/07/2016) described as ‘basically a monopoly’. The sale and use of consumables for automation platforms in the biosciences creates an economy of supply and demand that system users need to become adept at negotiating to get the best value products. The commercialisation activities related to system procurement, service contracts and consumables might seem like an unintended effect of policy maker investment in automation-driven synthetic biology. However, this is not the case. The 2016 strategic plan, *Biodesign for the bioeconomy*, states clearly that their proposed funding would create new businesses to supply the industry. At present, these automation system consumables economies are the most tangible example of the commercialisation effects of automation-driven synthetic biology.

In the next two sections, I review how informants at both sites reconfigured the five promissory narratives outlined above. Specifically, I present my evidence that questions about what counts as a legitimate method or a good result are implicated strongly with conceptions of identity, and the practice of embodied knowledge.

8.6 Attentive engagement and the making of amphibious researchers

When I say that researchers at my case study sites were attentively engaged, I mean that my informants were attentively engaged with their tools and with each other. As Ingold puts it, attentive engagement is 'a purposeful alignment of the novice's attention to the movements of others, and a harmonisation of that attention with the novices own movements so as to achieve … fluent performance.' (Ingold 1997: 111). From my own experiences as the novice in the RL, my performance was not fluent enough to keep the system functioning; it took Rosalyn's intervention to show me what I needed to attend to, to get the system functioning. If I am to push these insights a little, how is it that my informants judged the robots to be performing fluently? I considered if my informants' movements and the robots' movements needed to be harmonised to create a successfully functioning system. However, to draw this conclusion would be an over-simplification of what it means to be attentively engaged. A robot can never achieve attentive engagement because this is an affective experience. To be a good biologist or a good engineer carries emotional weight and to be an amphibious researcher means caring for and nurturing both robot and cell behaviour; it is not a reciprocal relationship.

However, relationships between human novices and human experts are reciprocal and, most importantly, the teaching of skills and harmonisation of action to learn how to use tools forms part of that reciprocity. The attentive engagement that people need to become competent members of a group involves skilful mimicry between novice and expert, and feelings of confidence and meaning become linked to the tools that users rely upon in their relationships. In this way, we can see that attentive engagement is about the ways that humans come to know their artefacts and their relations to and with each other through these artefacts. The five narratives above are conspicuous precisely because they pay too little attention to the relationship between technology use, training, skills and the formation of group belonging. Viewing automation as

simply the transfer of a task from a human operator to a machine lacks insight in to the reciprocal relationship between novices and experts, and how these relationships are deeply enmeshed within cultures of scientific practice.

As many STS scholars have argued, technologies are part of human relationships, technologies do not develop under their own momentum; they are shaped by society in the same way that society is shaped by technology (Pinch and Bijker 1984, Williams and Edge 1996, MacKenzie and Wajcman 1999, Wajcman 2006). By showing the affective character of the relationships my informants had with their systems and each other by being attentively engaged I see that mutual shaping does not coincide with mutual feeling; only people feel, as Ian at the AL confirmed, robots simply '… don't care.' (Interview 05/08/2016).

By focusing on the affective nature of the practice of developing automation systems in the biosciences, we can see that building a successful system is about building trust in methods, and confidence in results. For example, when Ian and Alex worked on planning and testing different functions of the robot system they experienced periods of 'storm' and periods of 'peace.' It was a frantic and, at times, stressful experience for Alex writing computer code and programming the robot system to carry out hundreds of different movements in response to Ian's ideas about what needed to be tested. During these 'storms' Ian, Alex and the rest of the AL team needed to have faith in each other, and trust in the tools with which they worked. For Alex, software engineering and synthetic biology offered space and excitement. He had trust in computer coding and robotics to help develop his career ambitions, and, in turn, to further synthetic biology's goals to heal, feed and fuel the world.

Just being an engineer is what made Alex happy; he wanted to solve problems and make other people's lives easier. The fact that he was working with biology meant that Alex felt part of an engineering identity that he viewed as involving a desire to solve problems, in an exciting new area, synthetic biology, that many other engineers had yet to find. Ian, in contrast, had a different sense of belonging, as someone that could make the science work. He defined that belonging by contrasting himself with the type of automation operator that he was not, someone that pushes 'go' at the start of the

day. In this observation, I recall Peter's comments in Chapter 5: clearly, Ian viewed his work as more than simply 'cleaning the urinals.' These insights address RQ2: What forms of boundary-work do laboratory users engage in when explaining the work of laboratory automation? Both Alex and Ian engaged in boundary-work (Gieryn 1983, Gieryn 1995) to play rhetorical games of inclusion and exclusion. Alex contrasted his sense of happiness at just solving other people's problems to the misery of competing in the academic sphere to generate new understandings. Alex wanted space and freedom to develop tools and he viewed academic biosciences research as crowded and with uncertain rewards.

Ian and Alex worked very closely together and shared knowledge and expertise to test their new system and prepare for potential customers wanting to pay for bespoke large DNA synthesis services. In this sense, then, both Ian and Alex were 'not academia as such' because both of them were following unusual career paths as postdoctoral researchers employed in software and automation engineering roles, but both also viewed these career paths as sufficiently lucrative and worth cultivating for future opportunities. However, as I have described, they had very different conceptions of their place among their group, and the potential career paths open to them. Alex, for example believed that the burgeoning interest in applying software engineering to the biosciences is where his future career would lead, whereas Ian looked increasingly towards a career in the pharmaceutical industry, where he believed his liquid-handling expertise would be most sought after. Therefore, my findings at the AL suggest that efforts to create new business models of customer-supplier relationships, from existing research collaborations and informal networks were not having predictable effects.

Furthermore, Tilda's vision of a serious and orderly DNA synthesis service provision runs counter to the playful and stormy experiences described by Alex. It seemed to me that Alex and Ian had to do lots of 'fiddling around' to find their way forward together, and to make the system perform in ways they each felt were good enough. Alex and Ian in particular recognised that the end goals of the AL service provision were perhaps less important than the knowledge they were generating in the process of setting the system up. Ian, as discussed, had set plans to use this knowledge to demonstrate his value to major users of laboratory automation systems, including large pharmaceutical

companies. Being an academic or an engineer was not a fixed state for Ian or for Alex. They each articulated and underlined different aspects of their skills and interests, depending on who they were addressing and in what context.

In this sense, both Ian and Alex, in different ways, sought to develop their own capacities and skillsets to promote ambitious career plans. In doing so, they were attentively engaged amphibious researchers navigating disparate group and individual identities. Although Tilda's descriptions of the AL posit these dynamics as a pathway from disorderly fiddling around to the serious business of creating a large DNA fragment synthesis service provision, I resist this interpretation. One of the key findings from my time with the AL is that for Ian and Alex to find out who they were and where they belonged both now and in the future, they each had to trust one another and their shared belief in the need for messiness in their partnership. Even as they each held different possible futures in mind, both for their likely career trajectories and for the value and legacies of the system they would leave behind.

Observing how Alex and Ian highlighted and minimised different skills for different audiences brings us back to what types of knowledge and skills are important for automation-driven synthetic biology. The next section considers these issues in relation to embodied knowledge.

8.7 Recognising the importance of embodied knowledge for automation-driven synthetic biology

My findings demonstrate that there are many ways to define success and failure, and that these are fleshed out in practice in different ways depending on the actors and the setting. Accordingly, users best placed to make those judgements are practitioners of amphibious working knowledge. Users practising amphibious working knowledge demonstrate their amphibiousness each time they engage their hands and fingers to intuitively direct the behaviours of their cells and their liquid-handlers. As described in Chapter 2, I see this intuitive bodily tacit knowledge, as a form of Mackenzie's (1999) 'fingerspitzengefuhl' or fingertip-feeling. Fingertip-feeling for the informants in my study was also part of who they were as competent researchers. Each of the key informants at both the RL and the AL were valued by the rest of their group, in part,

because they knew how to handle the machines. If a process stopped working, or a newer user needed to learn a technique using the platform, Rosalyn, Ian and Alex would be the first point of call. They each had a knack for knowing their system and that intuition and 'feeling for' their systems helped to shape their identities among their respective groups.

Given that informants at my sites developed a sense of belonging as part of their teams through this embodied knowledge, I now return to Collins' earlier discussions of tacit knowledge. Based on my research I find further evidence for Collins' argument that knowledge is not located inside individual human minds and that the body is not the original source of knowledge. However, Collins' focus on the collective nature of the conceptual structure of human lives leaves out an important part of how humans attach meaning to that conceptual work. As I have outlined above, for laboratory automation users meaning and emotion are often entwined. As Butler would say, all attachments to others are 'passionate attachments' and I would add that when people conceive of themselves and their relations to others they do so somatically; it is an embodied attachment too. Furthermore, it is only through an attentive engagement with a world of people and things that human beings understand this world and their place within it. The pleasures of learning skills and feelings of satisfaction and competence in displaying those skills cannot be separated from the engagement between groups and the tools and knowledge they share. The structures for understanding that engagement are certainly located at the collective level: they are part of the learned culture of a person in a particular place and among a certain group.

However, researchers experience this attentive engagement through the haptic sensitivities of the human body. The shapes of the actions that human beings take are polymorphic, which means the actions change according to the social arrangements, as described in Chapter 2. Each person attunes his/her body to other bodies through training and learning from other people, and the understandings that derive from this mutually shaping, bodily learning are collective. In this sense, Collins' project to demote the body and promote society proposes a division that is not practicable in the lived experiences of laboratory users. More importantly, this division between the

body and the collective impoverishes an understanding of how it is that human society is able to build and sustain understanding over time. In my view, collective tacit knowledge is unhelpful as a category because individuals cannot live collectively without embodiment. These insights provide understanding around what successful replication of human actions by a liquid handling robot look like for current laboratory users (RQ3). The somatic-collective distinction is not a helpful one because system builders and users rely upon their bodies to gather and share understanding about the unexpected behaviour of the biological materials they handle, and the robot platforms they design and use.

8.8 Conclusion

In this thesis I have analysed the ways that robots and automation in the biosciences at least and in current form, are becoming tangled up in the day-to-day lived experiences of a number of laboratory users. I argue that these lived experiences necessarily reconfigure the promissory narratives for laboratory automation and synthetic biology through the local conditions at each of my sites. My key finding is that to make informed judgements about proper functioning and how to fix failure in the system, laboratory users must make judgements about the right conditions, the right methods, and the right results. My empirical data demonstrate that these judgements of correctness cannot be made without an understanding of cell behaviour, an understanding of robot behaviour, and an understanding of the embodied and intuitive 'fingertip feeling' that is needed to simultaneously apply those understandings to maintain correct functioning.

Part of the battle for automation optimists is of course to train a new generation of researchers who will be at ease with the new automated techniques. Eventually, these 'new' users will become the mainstream experts and, intuitively, one might expect the use of automation to become as routine as manual pipetting methods are now, suggesting a 'natural' progression from one to the other based on generational preferences. However, the tensions and resistances I have found strongly suggest these intuitions may need to be revisited. My thesis has questioned the technological determinism in some policy and practitioner accounts that position ever increasing

automated liquid-handling as an inevitable outcome for the biosciences, particularly synthetic biology. I have done this by demonstrating that automation has many forms and by showing the multiplicity of potential futures for automation and synthetic biology. Moreover, I have provided extensive empirical data highlighting the crucial role for specialist amphibious knowledge in human operators to make automated liquid-handling work for current problems and priorities in synthetic biology. At present, there is a concerted effort to prove the value of automation, but the value of automation is not widely held, understood, or shared by academic bioscientists. Just as the future of the field of synthetic biology is still in the making, the role of amphibious working knowledge, and of automated liquid-handling as a driver for that future also remain open.

Some laboratory automation advocates are attempting to build research programmes and new facilities that will eventually have self-sustaining momentum but this is an explicit strategy that will be more or less successful for a number of reasons. I have offered some insights into those reasons in this thesis. However, my informants are not interested in converting others to have faith in automation. They care mainly if techniques work for their purposes and often remain agnostic on automation. I see the potential value of automation for improving laboratory techniques as firmly related to researchers' continued commitment to sustaining their amphibious knowledge. In doing so, it is users that make the systems work, and is it only by understanding how they make them work that observers can begin to understand how uneven the value and appropriateness of various forms of laboratory automation is for different researchers. My findings suggest that large-scale adoption of automated liquid-handling laboratory techniques is not an inevitable outcome in the biological sciences, but is instead one part of a struggle therein to define and redefine acceptable results and methods.

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Appendices

Appendix 1: Interview question guide

Questions to ask at interview:

Start with a bit about yourself, how did you get into this field, is there a memory of taking decision to become [x]?

Mentioned [synthetic biology, biosciences, life sciences, research, computing, programming, automation … … …] – how would you describe the field you're in now? Has this changed?

Could you talk a bit about kinds of skills needed in this field?

Where do you see the future of [molecular biology, synthetic biology etc]?

What are the easy wins or low hanging fruit in [x]? And what do you see as being more difficult to achieve?

If you were asked to speculate where the attention and resources [of group, institution, government, funding etc] should be focused in the next few years, what would you say?

What do you see as the real opportunities for [x]? What is it going to help with? What isn't it going to do? What expertise do you think you'll need to make it work?

More abstract questions -

What is science?

What is engineering?

[What is automation?] – if they mention this?

Do you see any changes to these categories, or the types of work a 'scientist' or an 'engineer' might undertake?

Speaking to others outside main actors:

Why people use robot platform (from other labs etc)? Do you get results you want? Find people exploring what platform can do and ask why Qs?

Ask others [at AL] – are you going to use [the AL]? Can overcome blockages? What does automation do, can it mean different questions get asked?

Informal chats with [AL], do you know about AL, will you use it etc. What will help with, what questions might help to answer?

Text miners - how get involved in project? What does text mining allow for in this context? How does reliability and robustness of scientific research get calculated? What are the benefits and limitations of using these approaches in the context of biosciences research findings?

Language in interview:

Want to understand the mundanity of research at my sites (as automation, robotics seen to take on some of that burden). Perhaps use ‘maintenance’ rather than mundane? So, how is the operation of the lab maintained day-to-day?

Appendix 2: Ethical review

University of Edinburgh,
School of Social and Political Studies
RESEARCH AND RESEARCH ETHICS COMMITTEE

Self-Audit Checklist for Level 1 Ethical Review

*The audit is to be conducted by the **Principal Investigator**, except in the following cases:*

- ***Postdoctoral research fellowships** – the applicant in collaboration with the proposed mentor.*
- ***Postgraduate research** (PhD and Masters by Research) – the student together with the supervisor. Note: All research postgraduates should conduct ethical self-audit of their proposed research as part of the proposal process. The audit should be integrated with the student's Review Board.*
- ***Taught Masters dissertation** work and **Undergraduate dissertation/project** work – in many cases this would not require ethical audit, but if it does (for example, if it involves original fieldwork), the student conducts the audit together with the dissertation/project supervisor, who keeps it on file.*

Potential risks to participants and researchers

1 Is it likely that the research will induce any psychological stress or discomfort? YES□□ NO ×

2 Does the research require any physically invasive or potentially physically harmful procedures? YES□□ NO×

3 Does the research involve sensitive topics, such as participants' sexual behaviour or illegal activities, their abuse or exploitation, or their mental health? YES□□ NO ×

4 Is it likely that this research will lead to the disclosure of information about child abuse or neglect, or other information that would require the researchers to breach confidentiality conditions agreed with participants? YES□□ NO ×

5 Is it likely that participation in this research could adversely affect participants? YES□□ NO ×

6 Is it likely that the research findings could be used in a way that would adversely affect participants or particular groups of people? YES□□ NO ×

7 Will the true purpose of the research be concealed from the participants? YES□□ NO ×

8 Is the research likely to involve any psychological or physical risks to the researcher, and/or research assistants, including those recruited locally? YES□□ NO ×

Participants

9 Are any of the participants likely to:
be under 18 years of age? YES□□ NO ×

be physically or mentally ill? YES□□ NO ×

have a disability? YES□□ NO ×

be members of a vulnerable or stigmatized minority? YES□□ NO ×

be in a dependent relationship with the researchers? YES□□ NO ×

have difficulty in reading and/or comprehending any printed material distributed as part of the research process? YES□□ NO ×

be vulnerable in other ways? YES□□ NO ×

10 Will it be difficult to ascertain whether participants are vulnerable in any of the ways listed above (e.g. where participants are recruited via the internet)? YES□□ NO ×

11 Will participants receive any financial or other material benefits because of participation, beyond standard practice for research in your field? YES□□ NO ×

Before completing the next sections, please refer to the University Data Protection Policy to ensure that the relevant conditions relating to the processing of personal data under Schedule 2 and 3 are satisfied. Details are Available at: www.recordsmanagement.ed.ac.uk

Confidentiality and handling of data

12 Will the research require the collection of personal information about individuals (including via other organisations such as schools or employers) without their direct consent? YES□□ NO ×

13 Will individual responses be attributed or will participants be identifiable, without the direct consent of participants? YES□□ NO ×

14 Will datafiles/audio/video tapes, etc. be retained after the completion of the study (or beyond a reasonable time period for publication of the results of the study)? YES□□ NO ×

15 Will the data be made available for secondary use, without obtaining the consent of participants? YES□□ NO ×

Informed consent

16 Will it be difficult to obtain direct consent from participants? YES□□ NO ×

Conflict of interest

The University has a 'Policy on the Conflict of Interest', which states that a conflict of interest would arise in cases where an employee of the University might be "compromising research objectivity or independence in return for financial or non-financial benefit for him/herself or for a relative or friend." See: http://www.docs.csg.ed.ac.uk/HumanResources/Policy/Conflict_of_Interest.pdf

Conflict of interest may also include cases where the source of funding raises ethical issues, either because of concerns about the moral standing or activities of the funder, or concerns about the funder's motivation for commissioning the research and the uses to which the research might be put.

The University policy also states that the responsibility for avoiding a conflict of interest, in the first instance, lies with the individual, but that potential conflicts of interest should always be disclosed, normally to the line manager or Head of Department. Failure to disclose a conflict of interest or to cease involvement until the conflict has been resolved may result in disciplinary action and in serious cases could result in dismissal.

17 Does your research involve a conflict of interest as outlined above? YES □□
NO ×

Overall assessment

If all the answers are NO, the self audit has been conducted and confirms the ABSENCE OF REASONABLY FORESEEABLE ETHICAL RISKS. The following text should be emailed to the relevant person, as set out below:
"I confirm that I have carried out the School Ethics self-audit in relation to [my / name of researcher] proposed research project [name of project and funding body] and that no reasonably foreseeable ethical risks have been identified."
• Research grants– the Principal Investigator should send this email to the SSPS Research Office (ssps.research@ed.ac.uk) where it will be kept on file with the application.
• Postdoctoral research fellowships – the Mentor should email the SSPS Research Office (ssps.research@ed.ac.uk) where it will be kept on file with the application.
• Postgraduate research (PhD and Masters by Research) – there is no need to send the Level 1 email. The ethical statement should be included in the student's Review Board report.
• Taught Masters dissertation work and Undergraduate dissertation/project work – there is no need to send the level 1 email. The dissertation supervisor should retain the ethical statement with the student's dissertation/project papers.

If one or more answers are YES, risks have been identified and level 2 audit is required. See the School Research Ethics Policy and Procedures webpage http://www.sps.ed.ac.uk/admin/info_research/ethics for full details.

Appendix 3: Access to Case Study 2

Chris Mellingwood (PhD candidate in STS) University of Edinburgh

Title: Investigating the engineering imagination in biology

Who is conducting this research?

I am Chris Mellingwood and this research is part of a PhD in Science and Technology Studies at UoE. The project is supported by a cross-College EPSRC studentship (linking the Schools of Engineering, and Social and Political Sciences). My research field looks at the social, historical and philosophical dimensions of science and technology.

I have three **supervisors**:

Dr Jane Calvert Prof Alistair Elfick Dr Pablo Schyfter

What is this research about?

I am interested in biological engineering, especially activities related to synthetic biology. Specifically I want to learn more about how automation is being used in synthetic biology laboratories, and what this might mean for both laboratory users and the future of biological and engineering research practices.

What is the proposed value of this research?

For me, understanding how existing laboratory users view automation is important. This is because the organisation of some laboratories is said to be entering a new paradigm through adoption of automated workflows. I want to find out how scientists use automation in their daily routines, and what forms of experimentation are made possible through varying technologies. Greater accuracy, enhanced reproducibility, and increased productivity are some of the promises being made for laboratory automation in biological research and engineering. I want to explore these issues alongside current lab users and, in turn, understand how human-machine configurations influence what it means to do laboratory work.

What research have I done so far?

Since Oct 15 I've been resident at [another UK-based institute, the Rhodes' Lab]. Several days each week I worked from one lab's office space, shadowing different lab members. A small number of one-to-one interviews are also planned. I have basic training to use some lab equipment, mainly operating demo protocols to transfer 96 and 384 well plates between liquid handlers, plate readers etc. I use anthropological methods, which are entirely flexible. Often, at [RL] I would work at my desk, accepting invitations to shadow different people as daily work plans allowed. At other times, I would spend the day at my desk only (working on papers, articles etc.). This strategy has been successful for embedding my work within the lab, contributing where possible, and not placing any unintentional strain on the lab's overall objectives.

How could I spend my time with the [Assemblers Ltd]?

I plan to use the above experience as a template for time spent with the AL. If available, I would request some desk space, working from that desk each week. Each month I'd collate notes and plan the following 4 weeks' work. Depending on progress, I could visit up to 3 times (see fig 1 below). One or two visits might be ample. This would make use of my available field work time (6 months), and look to capture early implementation and development of the [AL] platform.

What materials will I produce and how will they be shared?

I will take hand written field work notes, which will be typed up afterwards. Using these notes I may write papers or articles, reflecting on the observations made and linking to literature in the field of Science and Technology Studies (STS). At no time will my material identify the individuals I have visited: they will be anonymised in all public works. My final PhD thesis will be available through the UoE library website.

Contacts and further information

To get in touch please email C.R.Mellingwood@sms.ed.ac.uk.

Figure 1: Flexible timeline for [AL] lab ethnography

Appendix 4: Consent form

Institute for the Study of Science,
Technology and Innovation
The University of Edinburgh

Chris Mellingwood
C.R.Mellingwood@sms.ed.ac.uk

Supervisors: Dr. Jane Calvert
Jane.Calvert@ed.ac.uk
Dr. Pablo Schyfter
P.Schyfter@ed.ac.uk

Prof Alistair Elfick

A.Elfick@ed.ac.uk

Consent form

By signing this form you are agreeing to the following statements:

1. I understand that my participation in this study (see attached information sheet) is voluntary and that I am free to withdraw at any time, without giving any reason, without my conditions of employment or legal rights being affected.

2. I understand that my responses will remain confidential and that my data will be stored in accordance with the Data Protection Act (1988). I also understand that only anonymised quotes will be used in any published material and that if an individual is mentioned, a pseudonym will be provided to protect that individuals' identity.

3. I agree to be audio recorded during the interview and understand that a copy of the resulting transcript can be made available on request.

_____	_____	_____
Name of Participant	Date	Signature
_____	_____	_____
Name of Person taking consent	Date	Signature

Appendix 5: Information sheet

Institute for the Study of Science,
Technology and Innovation
The University of Edinburgh

Chris Mellingwood
C.R.Mellingwood@sms.ed.ac.uk

Supervisors: Dr. Jane Calvert
Jane.Calvert@ed.ac.uk
Dr. Pablo Schyfter
P.Schyfter@ed.ac.uk

Prof Alistair Elfick

A.Elfick@ed.ac.uk

Information for participants

PhD research project -The art of automation:
Comparing computing, biology and engineering imaginaries in UK biosciences research laboratories.

Dear [...],

Thank you for your provisional interest in my research project. This information sheet will help you to understand what this research is aiming to achieve, who is involved in the research, and what being part of a research project is likely to involve. Please read this information before deciding to participate. If any further information would be helpful please contact me using the email address above.

Who is conducting this research?

I am Chris Mellingwood and this is a research project for my PhD in Science and Technology Studies at the University of Edinburgh. My research field looks at the social, historical and philosophical dimensions of science and technology. I have three supervisors listed above.

What is this research about?

I am interested in synthetic biology as a discipline, and as a set of platform technologies. Specifically I want to learn more about how automation is being used in synthetic biology laboratories, and what this might mean for both laboratory users and the future of biological and engineering research practices.

What would involvement in this research mean for you?

There are several options for taking part in this research. I'd like to spend an extended period visiting your work space and learning more about what happens in day-to-day practice. This might involve me shadowing you during normal working hours. If possible, I'd also like to interview you and ask questions about your work and audio record this conversation, with your permission, to help with my later writing.

How will the information be used?

The research will form part of a PhD thesis and will be publicly available through the University of Edinburgh library. I may also use selected material for later conference presentations and publications in academic journals.

What happens next?

Please read the following consent form if you would like to take part in this research. If you have any further questions please contact me using C.R.Mellingwood@sms.ed.ac.uk

Thank you for taking the time to read this information and for considering taking part in this research.

Yours sincerely

Chris Mellingwood