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Engineering Research Teams: The Role of Social Networks in the Formation of Research Skills for Postgraduate Students

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Postgraduate supervision, Skills development, Social ties, Network structures, engineering, Performance-based research funding

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Introduction

Doctoral students need to acquire a range of generic and disciplinary focused skills. While the process of developing these skills can vary markedly, the characteristics of success in the knowledge economy are closely aligned with long standing research practices and output expectations. Although our argument primarily concerns the shifting landscape of postgraduate education in New Zealand, it is connected to broader consequences of the transformation towards knowledge economy directed outcomes for postgraduate higher education.

In this discussion, the definition of knowledge economy draws on Green & Usher (2003), whose framework recasts knowledge from an epistemological stance to an economic and productivist position (p. 38). The knowledge economy requires doctoral graduates to have skills that enable flexibility in employment, often referred to as generic skills, alongside core disciplinary competencies required for advanced research. Increasingly, tertiary funding pressures in the Australasian and European settings reward timely completion and outputs extending beyond more traditional theses. In this paradigm, knowledge becomes both an input and a measurable output (Green & Usher, 2003), with resulting pressures challenging the provision of doctoral programmes.

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We acknowledge that the modes of practice and the application of disciplinary research outputs differ markedly. To understand how doctoral students are acquiring their skills, we have focused on students from the 'hard' knowledge areas (Becher & Trowler, 2001). 'Hard' is used here not as a measure of difficulty, rather it refers to the presence of well-defined boundaries, theoretical structures and paradigms used to resolve questions. While all disciplines sit on a continuum, hard task areas are most often (though not exclusively) associated with quantitative methods. This label is characteristically applied to such disciplines as engineering, mathematics and the range of sciences (Becher & Trowler, 2001). This contrasts to 'soft' disciplines that encompass the humanities, social sciences and education, for example.

Drawing on the experiences of doctoral students in the hard discipline of engineering, we examine two aspects of their experiences with implications for skills development and supervisory practice in other areas. First, we explore the social structures that shape the environment in which students operate. Next, we examine the characteristics of academic socialisation in the broader discipline. Supervision and learning practices in engineering have the capacity to enhance generic skills development while at the same time buffer students from some challenges facing postgraduates from other disciplinary backgrounds. The concepts that emerge in this study arise from central tenets of postgraduate engineering research. Nonetheless, they contribute to the empirical evidence necessary to inform a vital debate on skills acquisition and supervision practices.

The Global Context: The Knowledge Economy and the Skills Agenda

The impact of the growth of governmental initiatives concerning the 'knowledge economy' on the PhD experience is an area of increasing interest in higher education research and policy (e.g., Usher, 2002; Green & Usher, 2003; St George, 2006; Davidson, 2007; Robert, 2002; Smart, 2007). While the objective of the traditional PhD was once principally about producing university academics, increasing demands for innovation and research-led entrepreneurship leave little doubt about the links between *knowledge* and *economy* (Davidson, 2007).

The role of the doctorate in this 'knowledge economy' partnership contributes substantially to the creativity and innovations that lead to the outputs emerging from the collective endeavours of students and their supervisors. This is most clearly evident in the hard disciplines, which have cultural practices that align well with the needs of the knowledge economy (Sampson & Comer, 2010). Yet the purpose of doctoral education is not solely oriented towards the production of new knowledge. Doctoral students must develop a range of transferable skills in order to participate effectively in this new context (Park, 2005). They must learn to negotiate the complexities of diverse research environments as well as to juggle their career aspirations and personal development objectives (Roberts, 2007).

Finding the most productive pathways to assist students in acquiring such skills is a vital consideration for PhD program developers. This becomes more important as doctoral candidate numbers increase and knowledge economy output measures (including completions) intensify pressures for change in postgraduate programmes (Park, 2007). In the UK, the mismatch of traditional PhDs to meet career requirements beyond academia has prompted specific policy attempts to redress this imbalance (Roberts, 2002). Researchers and academics worldwide are now examining the doctoral skills agenda (Davidson, 2007) alongside scrutiny of the concept of the traditional PhD as being fit for all purposes (Gilbert, 2004). In New Zealand, as yet there is has been no national initiative to redress this potential imbalance.

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Doctoral Landscape and Performance-based Research Funding in New Zealand

As elsewhere, there have been significant changes in student numbers and research funding for higher degrees in New Zealand. Since 2000, annual doctoral enrolments nationwide have climbed 32%, and the ratio of PhD students per full-time academic staff member has increased from 0.5 to 0.7 (Gerristen, 2008). Accompanied by a switch to a nationally administered Performance Based Research Fund (PBRF) in 2003, this has direct parallels to the UK's Research Assessment Exercise (RAE). The PBRF is a competitive system of allocating research funding, with a stated primary goal to encourage and reward excellent research in the tertiary education sector (TEC, 2006).

The PBRF model comprises three components: the level of external research income attracted by the institute; the research quality of staff (measured by individual outputs); and numbers of postgraduate research completions. Each component has a bearing on the subsequent national ranking of an institution and associated levels of funding. National policy has also shortened the length of time for which funding is provided, emphasising timely completion of PhDs. Funding, outputs and student completion have combined to become the foci for individual supervisors and institutions aiming to remain competitive in higher education. Moreover, the PBRF operates as the single strongest national policy instrument of the knowledge economy within the tertiary research sector.

Theoretical Framework

The concept of social capital originated partly to understand how features of social organisation – such as networks, norms and mutuality – can facilitate coordinated social action (Putnam, 1993). Shared activity improves the efficiency of society and provides the opportunity to resolve some of the issues individuals face in common. Accordingly, individuals use social networks as a resource to facilitate productive actions (Coleman, 1988). Learning communities are one kind of social community, and aspects of social capital theory have been usefully applied to understand the underlying social structures and organisation (Pilbeam & Denyer, 2009; Salaran, 2010).

Networks comprise both bonding and bridging ties and are the fabric of social relations. In his seminal works, Granovetter (1983) details the role of bonding and bridging ties[1]. Bonding ties are comprised of close social connections, they are defined by frequent and overlapping contact, and individuals within them form 'densely knit clumps of social structure'. Successful previous collaborations imbue these structures with 'social memories' that serve as 'cultural templates' for future action (Putnam, 1993). On the other hand, the experiences of acquaintances can provide bridges to diverse and heterogeneous social circles. Such bridging ties are not known by all within one's immediate circle and levels of engagement within them are considerably less (Granovetter, 1983).

Based on the premise that every individual has unique networks, bridging ties provide individuals with connections to seemingly separated parts of the social system. Such social bridges allow individuals access to other sets of experiences and expose alternative resources. In contrast, those with few bridging ties are confined to the relatively homogeneous views and limited information and resources of their immediate (social) world (Granovetter, 1983). While bonding social ties are essential to enable individuals to 'get by', the more scattered and wide-ranging bridging links foster

[1] Though Granovetter preferred the terms *strong* and *weak* ties, he used them interchangeably with *bonding* and *bridging*, respectively.

connections beyond the immediate community – necessary if an individual or a group is to 'get ahead' (Woodhouse, 2006, p. 86).

Mutuality describes the social norm of exchange relations, whereby individuals provide for each other with a common expectation that, at some stage (either immediately or the future), the goodwill will be reciprocated (Coleman, 1990). Mutuality can occur through direct or immediate exchange, or via more diffuse means, as this also depends upon the willingness of the wider community to reciprocate.

One further approach compliments the theoretical framework drawn on in this paper. Brown and his colleagues (1989) situate cognition and learning within the social and physical milieu of the learner. Cognitive apprenticeships start with the purposive modelling of tasks by senior or more experienced researchers. Students proceed to undertake responsibility for tasks in a guided fashion. Through repeated exposure, successful cognitive apprenticeships lead students to assume increasing responsibility for the success of their work. This process advances problem solving abilities and other fundamental skills. Students gradually learn to adjust to and accommodate the ambiguities that arise, thereby developing 'knowledge in activity' (Brown *et al.,*1989, p. 39).

This apprenticeship model positions students, initially, on the periphery of more complex understanding. As advanced by Lave and Wenger (1991) and supported by others (e.g., Hasraati, 2005), novices in a field are initiated into the practice of the discipline through repeated practice of tasks at the periphery. As skills and norms are acquired, students move from the periphery toward becoming fully legitimate and functioning members of the research group and disciplinary community.

Defining the Research

In the context of research on doctoral student development and the changing postgraduate landscape in New Zealand, this work explores two fundamental questions:

- How do the characteristics of academic networks foster generic skills acquisition for doctoral students in engineering?
- What disciplinary norms of practice support skill development in response to knowledge economy incentives?

To address these questions we have taken the following approach.

Methods

A total of 28 students – or 15% of the PhD population – were interviewed from departments within a College of Engineering: Mechanical, Civil, Chemical and Electrical. As researchers in academic development at the University of Canterbury, we have access to six years of university-wide postgraduate experience surveys that informed the scope of interest and questioning. Additionally, enrolment data enabled purposive sampling (in line with Miles & Huberman, 1994, p. 27) to derive a cohort of students who reflected the breadth of the postgraduate community of interest. Our final sample comprised 40% students from non-English speaking backgrounds (compared with 52% of the Engineering college population) and 30% women (in contrast to the 18% enrolled at that time). Sequential sampling allowed for both structural and conceptually driven factors to be considered. For example, we sought respondents at various stages of progress, from different sized research groups, and from collaborative or interdisciplinary teams or projects. This approach is in line with standard qualitative practice of the 'deliberate selection of theoretically important units' (Tolich & Davidson, 1999, p. 35).

A combination of focus groups and one-to-one, semi-structured interviews were used to explore the range of experiences that comprise skill acquisition during the PhD experience. The group format was employed earlier in the process to determine broader sets of issues. When possible, groups were arranged with students at the same stage of completion. This approach enhanced rapid *issues identification* by focusing on particular aspects of skill acquisition shared at distinct stages (e.g., the writing of the thesis proposal, preparation for the oral examination process, etc). Interviews were digitally recorded and transcribed. With the exception of the specific engineering department, participants were assured of confidentiality and anonymity prior to commencing the interviews.

Data coding was done manually, immediately following the transcription of the first group interview. This enabled early and continuous analysis in order to 'drive ongoing data collection' (Miles & Huberman, 1994, p. 65). During the initial stages and to adjust for bias, both researchers independently coded sections of the transcript, prior to collaborating on analysis. Once preliminary concepts were identified, interview format and 'shape' were adjusted. One-to-one confirmatory interviews followed. Discrepancies and areas of disagreement uncovered during the preliminary analysis could thereby be explored and clarified. Consistent with grounded methodologies (Corbin & Strauss 1990), data gathering concluded when no new concepts relevant to skills acquisition emerged.

Findings

What Generic Skills Do Students Value?

PhD students at all levels separately and repeatedly emphasised that a critical expectation of their own success was work that '*had application in the real world*'. Intrigued by this consistency, we proceeded to ask all students to comment on those skills considered crucial to achieving this objective. The two skills most commonly cited by students were *problem solving capabilitie*s and *strategies for finding and processing new information*. Central to engineering research is the notion that new PhDs have the capacity to problem solve at high levels. Though creativity and discoveries are important, they are made in the context of problem solving. What students set out to discover are solutions to real world problems that can '*make a difference*'. Alongside the thesis, students expected their doctoral work would produce something with utility. Additionally, students observed that skills in networking and collaboration, communication (of ideas and findings) and time management were also important to their success.

Preliminary discussions with students and academic staff revealed no formalised approaches that enabled students to systematically achieve these or other skill sets, with a few departmental-specific exceptions. Internationally, postgraduate programmes are increasingly committed to formalised generic skills training. For example, doctoral programmes in the United States typically require 12-18 months of coursework, some focused on generic skills acquisition. Since 2003, the nationally funded 'UK GRAD Programme' initiative has supported generic skills development through annual postgraduate training (Roberts, 2007; Richardson, 2007). However, in New Zealand both generic and research specific skills training generally take place only within the context of individual supervisory team practice and department guidelines. Consequently, the mechanisms by which students acquire generic skills are embedded in the social structures, academic organisation and practices of engineering. In the absence of formalised skills development programmes, student perceptions of the process tend to blur distinctions between generic and research-specific skills training.

Social Structure of the Environment – Networks and Ties

While not exclusive to engineering, team-oriented structures are predominant within

the discipline. From the outset, most doctoral students in engineering are assigned to a group or team. These research groups typically comprise some combination of masters and doctoral students, postdocs and academic staff. Often technicians and industry-related advisors are regarded as '*part of the group*'. For new PhD students, such structures and experiences establish teamwork as the norm.

Engineering doctoral projects commonly constitute one part of a significantly larger undertaking of work. Postgraduates typically commence their research on the understanding that they will be taking part in shared project. Even if they are the initial members recruited, PhDs on new projects subscribe to team-oriented expectations. As one such student noted in anticipation of being joined by other new doctoral students, '*you need more than one to make it worthwhile*'. With established projects, the boundaries of individual research projects have been predetermined and designed to fit into the wider objectives of the teams. As one student described this framework:

> *My topic is being worked on in the department. It is quite a big project…and so there are different aspects to the project like the electronics bit, the hardware bit, the reconstruction bit. So the whole project was already going and I have come in…to do a small part of it.*

Postgraduates enter environments in which group orientation, with pre-established networks, is the critical norm. Research teams create ready-made opportunities to develop pragmatic and functional bonding ties. Overlapping contacts between team members foster skills development as students engage in resolving common or shared technical or methodological challenges. This structure supports a wide range of generic and research-specific activities and enables students to learn the code of conduct of their particular discipline (Pilbeam & Denyer, 2009). Most notably, bonding ties provide opportunities for the transfer of tacit knowledge and the resolution of day-to-day issues (Golde, 2005):

> *Often the first thing is to bounce things off my friends, they're engineers and want to help, that's part of the skill you have to develop as a PhD...to resolve the day-to-day problems, I will talk to 'A' and other people who have been around a little bit longer. Then there is also 'J' who is a post doc.... So if 'A' doesn't really know, I will talk to her. She is like a level under my supervisor. We see her a lot.... And if she doesn't know, then I will go and talk to* [principal supervisor]*, or my other supervisor. It depends on the nature of what it is.*

Bonding ties offer valuable and enduring connections and create rich opportunities, yet their oftentimes homogeneous character can limit their usefulness. Potentially important criteria for the kinds of novel contributions, creativity and innovation demanded of doctoral research require heterogeneity of ideas, thoughts and skills (Pilbeam & Denyer, 2009). In the absence of formalised skills development programmes to draw upon, PhD candidates depend on the overlapping and mutually reinforcing aspects of these networks.

One student shared his approach of moving beyond the resources of his immediate group and using his weaker network ties to get himself '*unstuck'*:

> *I had a logistical challenge that my supervisor couldn't resolve. So I met with someone I knew in Geography who 'unstuck' me. I think* [as PhDs] *we do have to beat our own path to a certain extent.*

Participation at academic conferences is an excellent example of the capacity of bridging ties to access different sets of intellectual experiences and resources. In engineering, conferences are a beneficial pathway for students to learn the skill of networking in connection with their research-specific findings, and conference presentations are

promoted as vital to the doctoral experience. Nearly all students planned either attendance or presentations at upcoming conferences, or discussed those already attended.

Conference presentations were also aligned with co-authored or shared publications to follow, all of which constitute performance-based research eligible outputs. Hence departmental and supervisory motivations for fostering such practices is high. Funds for student attendance are typically allocated from research grants to provide such opportunities. Through this kind of support, doctoral students gain the experience of building wider professional networks alongside the more immediate utility of such interactions:

> *I was at a conference, and I saw a paper on a different topic but had similar aspects to it to my own work. And so I just talked to the person at the conference, took their card and sent them an email to say 'have you thought about this?' and 'what are your thoughts?' … And emails go back and forward, others say here are a few good ideas, some new things to look at. A lot comes from this.*

Bridging ties bring different clusters of research communities together. Yet effective ties do not depend upon group size or 'critical mass'. Research policy debates elsewhere were largely based on the premise that productive postgraduate education occurs in the context of a critical mass of research activity (Harris, 1996 as cited in Delamont *et al.*, 1997). While critical mass is important, in the absence of formalised training network structures matter more. They bridge the student experience beyond the immediate team and provide exposure to different sets of intellectual resources valuable to creative problem solving. Students' narratives reaffirm that fostering bonding ties allows individuals to 'get by', while drawing on bridging ties enables them to 'get ahead' (Woodhouse, 2006). It follows that 'getting ahead' must, in part, be a function of diverse and successful networks and the academic organisations that they evoke, rather than the critical mass of research groups *per se.*

Doability

A major responsibility of engineering supervisors is to establish clear project parameters that signal to students their research is doable (Sampson & Comer, 2010). This occurs more readily when students' research objectives are integrated into existing projects. When asked about their confidence in achieving project outcomes within allotted time and budgetary constraints, students' expectations were consistent:

> *It will get done.... My supervisor and a few other people had all sort of worked it out as a group, so I trust them.... With my project, it's just like really an overview of where we want to get to, the goals are clear and set and then it's just the details that are up to me.*

Beyond determining the ambit of projects, doability describes approaches designed to ensure progress to completion within the funded time period. By distilling the larger project into smaller, achievable parts, students develop strategies for immediate problem solving and acquire the skills necessary for developing outputs from their work. The common practice of writing up parts of research work for publication – particularly from an early stage in the student's candidature – illustrates this:

> *[What] my supervisor has told me is that 'each component or chapter of your thesis should be a paper, as you go through'. So that makes it easy, you could be writing your thesis as you go through, or you can be writing journal papers to build up your thesis....*

Students report that writing up '*doable chunks*' of work for peer review trains them early on to utilize wider intellectual resources. These approaches enable students to employ peer critique to test ideas:

> *It's a way of checking your ideas, a conference paper first, from that you get a lot of feedback from your peers, and then at that point you could modify that a little and then flick it off to a journal. It aids you so that when you are getting judged at the end and defending your PhD, the examiners would take that into account.*

Advanced PhD students were able to reflect upon how this process fostered confidence in the 'doability' of their projects within restricted timeframes. Generic skills, to include coherent argumentation, critical reasoning and clearly articulated written communication, must be developed before work can be published. These are also critical for the innovation and creativity demanded of quality PhD research. Further, publications arising advance the development of both performance-based eligible outputs and the doctoral thesis. Many students indicated that they were expected to publish more than once from their research prior to thesis submission, and some spoke of an understood '*three-paper plan'*. Hence this process encourages iterative problem-solving as part of the larger thesis experience, while simultaneously realising outputs from team efforts.

Repetition and Incrementalism

In developing independence and problem solving skills, engineering programmes emphasise repeated and staged exposure to different aspects of the research process. This staging advances postgraduates from generic to research-specific skills acquisition. The resulting repetition (sometimes returning null results) enables students to contextualise problems and practice techniques ahead of the requirement to apply them. Students are frequently assigned to work with other research group members who may be using similar techniques or experimental methods. They thereby begin to legitimate participation in their groups, while being exposed to and subsequently developing skills in bounded ways that anticipate subsequent research needs:

> *Before a student starts his own work, my supervisor gets them involved with other researchers and to follow the other colleagues. They help in the laboratory to run some experimental work. This may not be specific to the student, but it is relevant. In my case, I had to help another student with the 'shake table' test, and then later on I wanted to put something on the shake table and in that case I learned a lot three months or six months before I had to do this for myself*.

In line with the cognitive apprenticeship thesis, this exposure first models, then accelerates the acquisition of collaborative and research discipline specific skills. Through such apprenticeships, students begin to be legitimated as emerging researchers. Additionally, they are able to undertake 'dry runs' and practice techniques in preparation for future work:

> *The first six months I was reading and getting up to speed with the code that my group had developed and the codes used previously and then using the tools that they had developed. I just sort of analyzed a few patients that others in our group were interested in, it was sort of related to my project. I presented that work at conference first.*

Rather than explicit training, this comment reflects the accepted norm of building on and drawing from the work of others, as students move from novices to legitimate participants in the research process. The work this student describes led to his first conference paper, though the abstract was written and submitted before he joined the project. By the time this student repeated the conference experience, some 12 months later, there were marked changes in his confidence about his ability to do the work:

> *I wrote the abstract this time…and the results for that are along similar lines as that last conference we went to. But I have since had more time to repeat the work, to do better analysis. I know what I am doing now, and so the results are really good for that session.*

Characteristic of engineering 'practice', such repetition is central to cognitive apprenticeships. It creates the conditions for legitimate peripheral participation (Brown *et al.,*1989), which enable and accelerate the scaffolding of learning. As support for informal skills development observed in our participants, repetition serves them in multiple ways. It provides experience with techniques that will be inculcated in the course of students' research endeavours, initially while they are '*getting up to speed*' with existing knowledge, literature and techniques. Additionally, repetition enables supervisors to see more clearly where students might be predicted to go wrong, while at the same time providing the opportunity to develop 'knowledge in action' (Brown *et al.,*1989).

Although repetition sometimes leads students into blind alleys, it nonetheless helps advance future success:

> *Sometimes you 'work' something for weeks and find out its useless. I think in a way it is grossly inefficient, but that 'finding things out' is half the point, that's part of what it means to be a PhD. That problem-solving is an underlying skill you develop. If you had all the answers you wouldn't have that learning process.*

Through the processes of repetition, students intrinsically resolve problems *in situ*. Thus, as Brown *et al* (1989, p. 36) note, 'the problem, the solution, and the cognition involved in getting between the two cannot be isolated from the context in which they are embedded'. A doctoral student's comment reinforces this concept:

> [The blind alley] *is not so much about getting a null hypothesis, it's more about establishing the processes for analyzing. Because we had a rough idea about what we were aiming at...and so far that has been borne out but the method of analyzing the data and going through the process has been more important. It's not that it didn't get the results that I wanted, it's just that it was not the right way to go about it for example.... I have learned a fair bit.*

Characteristics of repetition establish and extend the practice of problem solving in incremental ways. Indeed, the concept of incrementalism aligns with the way in which knowledge is produced in the engineering model. As Delamont *et al* (1997) have argued, the production of 'scientific knowledge' is rarely associated with paradigm shifts or major discoveries. Instead, the vast majority of work emerges as a consequence of the small, incremental and repeated labours of individuals. As a postgraduate notes:

> *It's an evolutionary process, you sort of learn how, bit by bit.... It's a trial and error process, and you hit brick walls and then move beyond* [the problem].

Alongside developing their own work in team-based models, individuals provide findings to the outputs of the wider team. The process of experimentation (and hypothesis testing) contributes as much to the production of knowledge as it does to the development of strategies and skills for resolving dilemmas. Moreover the incremental strands of knowledge, produced by individuals, contribute to the formation of the 'collective rope' of the research team. Interwoven, overlapping, reinforcing and durable, its overall stability and continuity rely on the existence of a collective (Hacking, 1992). Through incremental growth in understanding and ability, the solution 'becomes apparent in relation to the role it must play in allowing activities to continue' (Brown *et al*., 1989, p. 36).

Mutuality

Mutuality is woven throughout the practice and narratives of engineering postgraduates and situates the acquisition of skill development within the discipline. The most obvious example here is co-publication, where students gain from preparing research for publication, and supervisors add to their evidence portfolios and satisfy performance-based output measures:

> *[My supervisor is] pretty good. You write it as best you can and send it up to him, and he'll make a few changes or whatever. And then basically, if I don't agree with him, he's pretty receptive about changes.... He's quite good at publishing and getting things out. Just look at the list of publications on his webpage.*

Though co-publishing is a more overt example of mutuality, its benefits extend beyond the shared productive activity of writing for publication. Mutual gains, via assistance on projects and tasks, are commonplace for many junior researchers working on the periphery of their teams. Through the staged exposure that develops from assisting others, they learn valuable skills and other related codes of practice, as well as gain additional information and data that may subsequently benefit their own research.

Mutuality can also develop from engagement with industry partners. As the following postgraduate notes, when an industry research partner contributed additional funding to test a particular component:

> *There is some testing coming up, and it's got nothing to do with* [my project]. *But for two weeks I am going to set up and run the work for* [industry partner]*...and I don't know if there is something that might come out of that that I can use for my project. So I'll get the results for them, and we've got an agreement that I can use the results in my PhD. Unless it's something that doesn't really apply to what I am doing and then I wouldn't use the results. But I would run it for them anyway.*

As opportunities arise throughout candidatures, mutual benefits accrue to members of the networks. Central to the concept of mutuality is exchange, which is often diffuse. For example, one senior student describes being sufficiently abreast of his research area such that he was meeting with his supervisors to share documents he had prepared. His express objective was to *'bring them up to speed'.* Having become the team's *expert* in this area, he accompanied his supervisor to meet with potential industry partners abroad and secure ongoing funding. Here we see multiple exchanges in effect. First is the exchange of skills – the research student apprentice has developed and provides the team's expertise in a specific area. Initially benefiting from the work – and the funding – provided by earlier team members, the doctoral student then becomes responsible for ensuring follow-on funding of the research team. This student is unlikely to benefit directly from such funds. Yet as a fundamental tenet of operating within a collective, mutuality reinforces the continuity and stability of the process.

Discussion

In 'knowledge economy' approaches to university rankings and funding models, the mechanisms whereby PhD students acquire generic and research-focused skills are of increasing importance for programme strategies. Upon commencing this project, we expected to find significant and well-ordered procedures supporting engineering students to develop their skills in problem-solving, strategies for taking in new information,

networking and the communication of ideas. Instead, we found particular characteristics of academic structures and supervisory practice contributing to student learning in ways that have broader implications for postgraduate research. This is particularly true with respect to the resulting networks that develop and enhance more formalised skills development approaches. Previous research in the 'soft' disciplines reflects similar networking opportunities, to include postgraduate peer support groups (Devenish et al, 2008) and multi-disciplinary writing groups focused on research outputs (Cuthbert, Spark & Burke, 2010).

In accordance with research on network structures, engineering doctoral students repeatedly emphasised the value of both bonding and bridging social ties in the acquisition and development of generic skills. In shared research tasks, bonding ties support knowledge transfer and tacit skills development. Bonding ties also develop the kinds of valuable and enduring connections key to sustaining mutuality, within universities and into industry. As problems extend beyond the capacity of individuals to address within their research groups, bridging ties foster extended access to diverse intellectual resources and problem solving approaches.

Student feedback indicates that the most effective supervisory processes enable them to establish networks for resolving dilemmas through shared instead of individual approaches. Effective and extended networks – with multiple opportunities for connections – produce research teams skilled to meet the demands of the knowledge economy. Therefore, the networks – not the mass – are critical, and the balance of their structure must be considered more carefully. This is even more vital with increasing numbers of multi- and interdisciplinary PhD programmes.

Further, there is considerable alignment between the way the academic discipline of engineering functions and the current organisation and performance incentives in New Zealand doctoral education. Engineering doctoral students are initiated within a culture characterised by research practices that embrace repetition and doability. Skills and understanding are developed incrementally – and knowledge is produced similarly. PhD students repeatedly established that a 'virtuous circle' exists based on these characteristics. Mutuality helps to ensure that students and supervisors alike are rewarded for incremental endeavours. In a discipline driven to solving problems, iterative approaches are normative, and frequent outputs communicating incremental successes are well served by knowledge economy mechanisms such as PBRF. Producing peer reviewed outputs enlarges the capacity for research teams to attract external funds, which in turn generates further support of graduate students (via research projects), and so on. The mutually reinforcing aspect of the circle makes it 'virtuous' to all within the discipline it serves.

Conclusion

As engineering PhD students demonstrate, disciplines based upon incremental progress and collaboration can have vastly different supervisory and mentoring practices, yet still thrive under performance-based funding models (such as PBRF, the UK's RAE, or similar pressures). For hard task areas, such as engineering, the shift to an outputs oriented and incentive-based approach required negligible changes to existing practice. As one engineering academic noted about this very issue, '*We'd be doing this anyway*.' Consequently, this sees the discipline well-positioned to be sustained in New Zealand's current funding landscape.

In contrast, 'soft' disciplines emphasising individual discovery or single-authored manuscripts can be challenged by output-focused research funding structures. Hence, lessons can be learned from the practices detailed above. To avoid being disadvantaged, soft disciplines may require more focused interventions. As others have identified, these

interventions can take the form of writing groups (Lee & Boud, 2003; Cuthbert, Spark & Burke, 2010), peer support groups (Devenish et al, 2008), multidisciplinary research teams (Yates, 2007), or similar initiatives that emphasise collaboration and network building. One focus of future research will be to explore how new initiatives in these directions assist and advance postgraduate supervision and output production in connection with knowledge economy imperatives.

As a number of cross-disciplinary and interdisciplinary collaborations involving engineering and other fields demonstrate (e.g., bioengineering and medical engineering), we are heading into a future that requires more integrated responses to research problems. Beyond size or critical mass of research group numbers, this study has shown that it is the composition of networks that enables effective skills development alongside research practices, as individuals resolved their own challenges through collaborative strategies. The rich disciplinary texture of the academy must be maintained if we are to produce a diversity of graduates skilled to take up these challenges. In scrutinizing the skills debate within our own PhD programmes, New Zealand is a 'late adopter' nation. The doctoral student comments and follow-on analysis of this study contribute much needed empirical evidence necessary to inform future discussions.

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