Using multidimensional scaling to organize expected outcomes of engineering education

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Structured Abstract

BACKGROUND

Standard setting organisations such as the Australian Qualifications Framework Council, Engineers Australia, the Australian Computer Society and the Australian Health Practitioner Regulation Agency (AHPRA) all generate comprehensive lists of expected outcomes, which must be demonstrated at accreditation time.

PURPOSE

In this exploration we take as a given the richness of the work that has gone into the generation of these lists of expected outcomes. However, we invite the reader to reconsider the way these outcomes can be organized and also to consider the implications for program and curriculum design.

DESIGN/METHOD

17 academic staff were asked to judge the proximity of the 16 Engineers Australia Stage 1 Competencies relative to the other 15 (120 evaluations each). These data sets were then processed using the multidimensional scaling algorithm, Permap, to produce a series of perceptual 2D maps of the relatedness of each of the 16 competencies. An average map was also produced.

RESULTS

There was a consistent view that the design elements of competency (2.1, 2.2 and 2.3) lie at the centre of the perceptual maps, with 2.4 (project management not far away). These elements relate most closely to all the other elements of competency. Two other clusters were clearly identified: the STEM cluster (1.1, 1.2, 1.3) and a ‘social science’ cluster of communication, teamwork and self management. Other elements of competency were less clearly aligned.

CONCLUSIONS

Initial analysis and modelling of the perceived relationships between the many expected outcomes of engineering education suggests a rethink for program design, with a focus on engineering design. The perceptual maps raise questions of organisation of the competencies; the current three groupings used in the Competency Standard do not reflect the relative importance of the competency clusters.

KEYWORDS

Engineering competencies; multidimensional scaling; threshold learning outcomes; project based learning

Expected outcomes in engineering education

From 2015 onwards, all Australian qualifications are required to meet the expected 'learning outcome descriptors of the Australian Qualifications Framework (AQF, 2013, page 103). For engineering education, this means the expectation that each degree meets a set of 'learning outcome descriptors', usually at AQF8 level, Bachelor of Engineering (Honours).

Such a large scale change provided both the need and political consensus to confront a myriad of expected outcomes in addition to Engineers Australia's 'stage 1 competency standards'. In addition to the more generic 'graduate attributes' individual universities may pursue, a diversity of expected outcomes was also apparent within each engineering faculty.

For example, one program at RMIT organised expected outcomes under the three headings of "technical", "integrative" and "professional". Some engineering Schools were considering MIT's 'CDIO' framework, which clusters expectations under four headings "*technical knowledge and reasoning", "personal and professional skills and attributes", "interpersonal skills: teamwork and communication"* and the *"Conceiving, Designing, Implementing and Operating (CDIO) systems in the enterprise and societal context*". Another approach divided dimensions of engineering capabilities into two sub-categories: organisational and individual. "Organisational capabilities" included communication and leadership, cultural adaptation, sustainable practice & organisational and management. "Individual capabilities" included diagnostic, research and development, strategic and imaginative & analytical and systematic.

When confronted with such a large diversity of expected outcomes, an appealing notion is to apply 'mapping'. However, normally, the associated artefacts of such mappings are tables, rather than maps. Whilst ranking provides a degree of order, there is a tendency to accept, as given, a proliferation of categories.

This proliferation of categories of expected outcomes is not a challenge unique to the study of expected outcomes of engineering education. In vocational education, Australia's eleven Industry Skills Councils also face the challenge of bringing together long lists of expected outcomes in so-called Training Packages. A 2008 OECD report on these Training Packages (Hoeckel et al, 2008, page 35) found that broad consultation and endeavours to accommodate a range of interests and concerns tends to lead to expansive lists (see also Wheelahan, 2012).

Similarly challenged, the Australian Computer Society, responsible for accrediting Information Technology education programs, uses the Skills Framework for the Information Age (SFIA) which defines 96 professional IT skills, organised in six categories, each of which has several subcategories (SFIA Foundation, 2014).

Whilst the 'wisdom of crowds' may support committees' abilities to generate comprehensive lists of expected outcomes, a coherent, designed taxonomy requires clarity regarding the relationships between constructs (see also Stegmuller (1976), Smith (1990), Love (2002) and Hedden (2010)). This challenge is often apparent in workshops when participants are asked to provide input on butcher's paper. Whilst the facilitator of such workshops can generally draw out patterns from the contributions of individuals or groups, it is conceptually more challenging to translate an eclectic range of views into a coherent framework.

Challenges of a coherent taxonomy or framework

Gould (1981, page 158) noted that the development of taxonomies is contentious, as "the world does not come to us in neat little packages". For the purposes of framing expected outcomes from engineering education, an effective taxonomy should generate broad consensus as to which category any single expected outcome would fall under. Not only should the taxonomy be commonly understood, the taxonomy's qualities such as sequence, weight and relative status should be based on informed rationale. Such coherence in a taxonomy of expected outcomes in turn informs curriculum design calibration, such as the optimal sequencing of four years of study for the engineering degree. Winston Churchill noted the influence of structure on action when he stated that "*we shape our buildings and afterwards they shape us*". Kahneman (2003) elaborated on the power of framing - 'the basic principle of framing is the passive acceptance of the formulation given'.

Engineers Australia's three 'stage 1' competency standard headings 'shape' education in a particular manner. EA's sequence starts with (1) knowledge and skill base, then (2) engineering application ability and finally (3) professional and personal attributes. Becher (1990, page 33) suggested that, whether implicit or explicit, arguments about knowledge are often guided by metaphors. Engineers Australia's sequence, if going by the above three headings, suggests what Neumann et al (2002) described as a linear and hierarchical discipline, building up brick by brick towards contemporary knowledge. This sequence implicitly influences engineering curricula, which usually begin with foundational technical knowledge and proceed through applications to professional practice.

The foundation metaphor may resonate with civil engineers, but Goldman (1995, p 222) noted that metaphors about knowledge have shifted from the static logic of 'foundation' and 'structure' to dynamic properties of networks, webs, systems, fields and topological metaphors that describe relationships. This view of the world was also taken by the inventor of the World Wide Web, Tim Berners-Lee (2000, page 12), who suggested that *a piece of information is really only defined by what it's related to, and how it's related. There really is little else to meaning. The structure is everything*. The significance of 'framing' information in context is elaborated upon by Starbuck and Milliken (1988) and De Martino et al (2006).

In this exploration we aim to improve the classification of expected outcomes of engineering education by probing the perceived relationships between the sixteen competency standards of EA. This data is then used to consider which theories may account for the variety of observations (Hempel, 1965, Faust and Miner, 1986). An example where such progress has been made is in the study of personalities. Here, a myriad of models existed until scientists came up with 'the big five'. In engineering education, we do not have a particular number in mind, but are confident that there is scope to discover a coherent constellation numerically between the three headings and the sixteen competency standards.

Exploring the relationships between EA's outcomes

17 academic staff with a leading role in engineering education were asked to judge the *adjacency* between each pair of the Engineers Australia's 16 competency standards on a 10 point scale (zero being identical and 10 being far apart). The aim was to understand subject experts' judgments of the relationships between these sixteen constructs. This is a symmetric matrix with zeroes along the leading diagonal.

Kelly (1955, 1969) pioneered a mathematical approach to psychology, relating geometry to psychological space. Coombs (1958), Shepard (1962) and Kruskal (1964) developed the ability to model otherwise abstract areas of analysis. Algorithms handling increasingly large amounts of data continue to evolve. Borg and Groenen (2005, page 5) propose that multidimensional scaling can be used to help researchers see structures in data. Nicherson et al (2012) suggest this approach can provide a grounded alternative to ad hoc approaches to organizing taxonomies.

For this exploration, we used the multidimensional scaling program Permap (Heady and Lucas, 2010). The fundamental purpose of Permap is to uncover hidden structure that might be residing in a complex data set (Heady, 2010). The sixteen subject experts in engineering education were asked to rate the perceived proximity of Engineers Australia's sixteen competency standards relative to one another. A low rating signified 'close' proximity, a high rating signified 'distance'. Each respondent provided a total of 120 ratings each (16x15/2). Using 'Permap', the rating data was converted to perceptual maps for each of the 17 participants, as well as a combined map based on the averaged data.

The algorithm used in Permap seeks the lowest average tension in the links between the nodes in two dimensions. Consequently, nodes that have been judged by the participants as being far apart are generally far apart when projected onto a two dimensional plane. Nodes judged to be similar will, of course, be closer together on the map.

Figure 1 shows a sample of the average ratings of 17 participants. For example, '*effective team membership and team leadership'* is rated, on average, as being 'distant' (8.9) from '*comprehensive, theory based understanding of the underlying natural and physical sciences…*', while somewhat closer (6.4) to '*Understanding the scope, principles and norms of engineering practice*'. Aiming to gain a rating from all 16 interrelationships, a total of 120 ratings were provided by each of the 17 participants.

Creative, innovative and pro-active demeanour.	8.2	8.6	8.1	7.2	7.4	7.9
Professional use and management of information.	8.4	7.9	7.7	6.1	7.6	6.6
Orderly management of self, and professional conduct.	8.8	9.0	9.0	7.0	7.1	6.6
Effective team membership and team leadership.	8.9	8.7	8.6	8.4	6.6	6.4
	Comprehensive, theory based understanding of the underp natural and physical sciences and the engineering fundam applicable to the engineering discipline.	Conceptual understanding of the, mathematics, numerical analysis, statistics, and computer and information sciences which underpin the engineering discipline.	In-depth understanding of specialist bodies of knowledge w the engineering discipline.	Discernment of knowledge development and research direc within the engineering discipline.	Knowledge of contextual factors impacting the engineering discipline.	Understanding of the scope, principles, norms, accountabil and bounds of contemporary engineering practice in the sp discipline.
	KNOWLEDGE AND SKILL BASE					

Figure 1: Sample of averaged proximity data

Figure 2 shows the perceptual map for the averaged data. Although the 17 individual maps showed remarkable differences in relation to the perceived interrelationships of these expected outcomes. The averaged data revealed the following clusters:

1. Design: 2.1 [METHODS], 2.2 [TOOLS], 2.3 [DESIGN]
2. STEM: 1.1 [SCIENCES], 1.2 [MATHS], 1.3 [DISCIPLINE]
3. Social sciences: 3.2 [COMM], 3.5 [SELF MNGT], 3.6 [TEAMS]
4. Research: 1.4
5. Information management: 3.4 [INFO MNGT]
6. Context of Engineering practice: 1.5 [CONTEXT], 1.6 [PRACTICE]
7. Project management: 2.4 [PROJ MNGT]
8. Ethics and personal accountability: 3.1
9. Innovation: 3.3

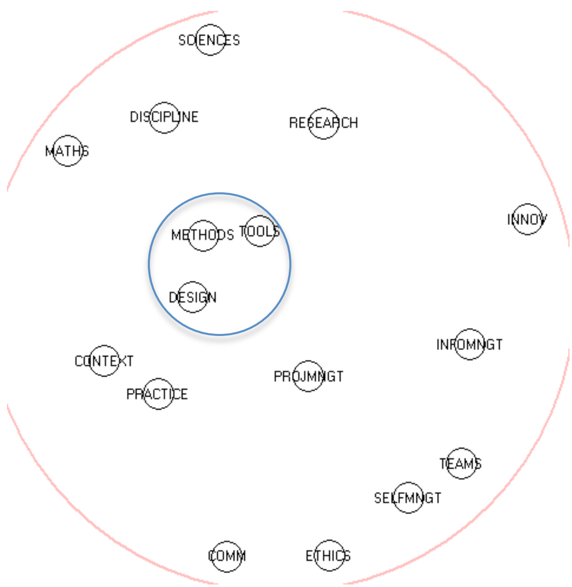

Figure 2: Perceptual map of average of all data

Analysis of the patterns in clustering revealed the following key patterns:

Centrality of an EA's '*engineering application abilities*' cluster

Perhaps unsurprisingly, the majority of the seventeen participants rated EA's four 'engineering application abilities' (2.1, 2.2, 2.3 and 2.4) as closely related and in the middle of their constellations. In the resulting perceptual maps, these four expected outcomes were either clustered, or rated as close to identical (2.1 and 2.2 were often rated as near synonymous). Project management (2.4) is on average rated as a distinct construct, but the other three are generally clustered closely. From an educational perspective, these would typically be taught through a 'project based learning (PBL)' part of the curriculum, e.g. through design projects or design and build projects.

Whereas Engineers Australia 'sandwiches' this PBL cluster between the preceding 'knowledge and skill base' and the subsequent 'professional and personal attributes', this initial data suggests that expected outcomes of engineering education is better represented as a solar system that circles around the engineering application elements (2.1, 2.2, 2.3).

PBL provides opportunity for a learning environment which develops the ability to think critically, and solve problems and fosters the development of skills such as research, teamwork, written and verbal communication and life-long learning skills (Duch et al. 2001). Accordingly, these learning opportunities enable and encourage the development of other key expected outcomes, suggesting that engineering curricula should be built around this central activity, which justifies the approach used at RMIT and elsewhere of a PBL spine through all years of the engineering programs.

However, whilst the perceptual maps of the 16 subject experts show more than three clusters, the main consistency amongst the 17 perceptual maps was the centrality of the PBL cluster. The other expected outcomes were located in a wide range of positions relative to this PBL cluster.

Applied social sciences cluster

Project management (2.4) is on average positioned between the PBL/design cluster and what could be titled as an 'applied social sciences' cluster, which includes communication (3.2) and management of self, information & teams (3.4, 3.5 and 3.6). Ratings show that these are perceived as distinct (but clustered) constructs.

STEM cluster

Notably, in most perceptual maps of individual contributors, as well as the averaged maps, the 'interpersonal' cluster is rated as opposite to what could be termed a STEM cluster, including elements 1.1, 1.2 and 1.3. This is the foundational knowledge and skills of mathematics, computing and the engineering sciences.

The asteroid belt

Apart from these three distinct clusters (design, STEM and social sciences) there are several other factors in close orbit around the triple sun of engineering practice. These include element 1.5, the external contextual factors relevant to engineering problem solving, such as sustainability, and the internal business factors of engineering practice (element 1.6), which are rated as closely aligned. Also included is innovation and research. Together, all of these are judged as more central than teamwork and communication, which is an interesting view. Future data collection among practising engineers might yield a different result.

While context (1.5) and practice (1.6) are aligned together, the distance perceived by academics of these two elements from the other four 'knowledge and skills base' elements assigned in the Stage 1 Standards is clear.

An emerging circumplex model of engineering capabilities

Quinn and Rohrbaugh (1981, 1983) interpreted their multidimensional scaling to create a circumplex model. Strack et al (2013) provide a range of examples and clarify the scientific validity of such circumplex models.

The expected outcomes of engineering education are centred around the application of engineering (2.1, 2.2, 2.3 and 2.4). Being 'central' in a perceptual map generated by MDS means that the other constructs provide context to these practice skills:

2.1. Application of established engineering methods to complex engineering problem solving.

2.2. Fluent application of engineering techniques, tools and resources.

2.3. Application of systematic engineering synthesis and design processes.

2.4. Application of systematic approaches to the conduct and management of engineering projects.

Communication, ethics and management draw on applied social sciences (sometimes called 'soft' skills), which are contrasted with the 'hard' sciences. The STEM enabling sciences include:

1.1. Comprehensive, theory based understanding of the underpinning natural and physical sciences and the engineering fundamentals applicable to the engineering discipline.

1.2. Conceptual understanding of the mathematics, numerical analysis, statistics, and computer and information sciences which underpin the engineering discipline.

1.3. In-depth understanding of specialist bodies of knowledge within the engineering discipline.

Questions of sequence

The perceptual map of one participant (Figure 3) accurately mirrors Engineers Australia's 'stage 1' sequence. Here, the classic 'foundation' of the sciences (1.1) maths (1.2) and discipline knowledge (1.3) is at the top of the diagram. The practice components lie at the heart of the diagram (Practice, Methods, Tools, ProjMgt). Context (1.5) is nearby. Design and Research are a little further removed towards the STEM group. Innovation is an outlier, with links to tools, and the social skills are clustered at the bottom.

A contrasting perceptual map is shown above. Here, context (1.5), practice (1.6) and ethics (3.1) are clustered, perhaps unsurprisingly since they represent the social dimension of engineering. Tools, Methods and Design cluster with Research. The social skills are again clustered on the right (Teams, Communication, ProjMgt and SelfMgt). Innovation lies further out, oddly not linked to design. The STEM cluster is on the top left.

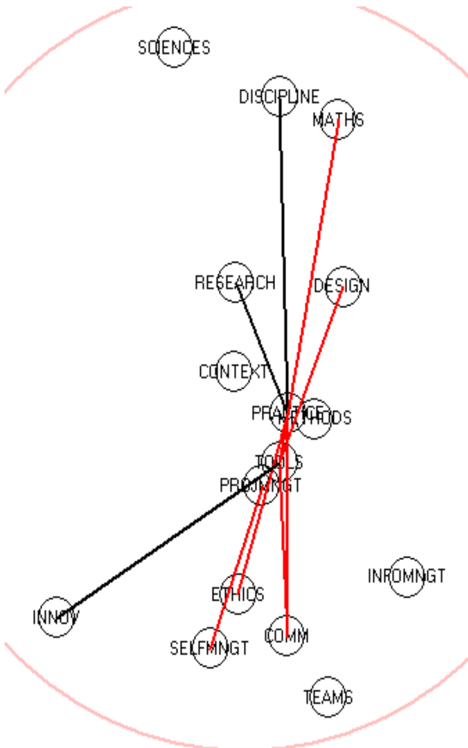

Figure 3: Individual map 1

Another perceptual map (Figure 4) is consistent with the narrative of the Threshold Learning Outcomes for Engineering and ICT (Cameron & Hadgraft, 2010), which commences with understanding the context of the problem / project (TLO1/CONTEXT). The Design cluster is in the centre, representing TLO2 (design and problem solving). TLO3 is the Sciences (1.1), Maths (1.2) and Discipline knowledge (1.3) which inform the Tools (2.2). TLO4 is the social skills of teams, communication and project management, while TLO5 is self management.

Limitations and further research

This analysis was based on 120 ratings per person in relation to the proximity of each of the 16 Stage 1 Competency Standards' 'elements' of competency. It is acknowledged that exclusion of the detailed 'indicators of attainment' (that are associated with each of the elements) in the analysis may have led to each participant making their own interpretations of what each element entails, based on the overarching 'title' given to each element. It is likely that participants would have used prior knowledge and experience to first define for themselves what each element involves, before rating each in relation to each of the others. This is apparent in the diversity of ratings.

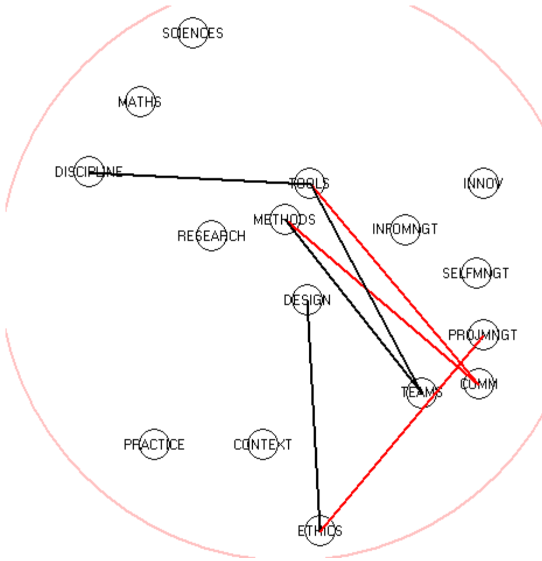

Figure 4: Individual map 2

While this does allow for rich data (taking into account individual participant input), analysis based on Engineers Australia's 94 'indicators of attainment' could provide a more standardised approach to interpret the proximity of each of the competencies, whereby each participant would start with a consistent understanding of what each element entails.

Visualisations techniques are making great strides. For example, Leydesdorff and Rafols's (2009) visualisation of cognate areas can be explored in http://idr.gatech.edu/. Creating such a perceptual map of expected outcomes of engineering education could facilitate a more considered organisation, whilst potentially avoiding a premature freezing of concepts (see also Larkin and Simon (1987) and Goel (1995)).

Maps can be enriched by other metadata; providing potential insights into the cognate areas are the Dewey Decimal Numbers, as well as the ASCED codes tied to courses or units. Once established, Chen (2004) illustrates how multidimensional visualisations can provide insights into what can be described as 'landmarks' and 'intellectual turning points'. Engineering faculties are generating more data linking expected outcomes with assessments, which could also be used for cluster analysis.

Alternatively, it might be interesting to simplify the analysis, recognising the clusters that have already been identified plus those unaligned elements that are not yet well identified.

1. Design: 2.1, 2.2, 2.3
2. STEM: 1.1, 1.2, 1.3
3. Social sciences: 3.2, 3.5, 3.6
4. Research: 1.4
5. Information management: 3.4
6. Context of Engineering practice: 1.5, 1.6
7. Project management: 2.4
8. Ethics and personal accountability: 3.1
9. Innovation: 3.3

Reducing the data collection from 16 to 9 drastically reduces the effort required by the participant from 120 evaluations to 36, a reduction of effort of a factor of about 3.5. We may be able to crowd source some data collection through a facility such as LinkedIn to collect 100s or 1000s of data points to get a clearer idea of these factors.

Implications for Curriculum Design

Although this is a preliminary analysis, some clear clusters have emerged within the 16 competencies: (i) engineering design (ii) underpinning STEM/disciplinary knowledge, and (iii) teamwork, communication and self-regulation. The question for us as engineering educators is 'how do our current curricula reflect these clusters, particularly engineering design?'

Most engineering curricula put enormous emphasis on the disciplinary knowledge with design considered as an add-on rather than as the central activity of the curriculum. This varies by discipline. The 'real education' is still considered to be teaching the disciplinary fundamentals rather than teaching engineering practice (Goldsmith, Reidsema, Campbell, Hadgraft, & Levy, 2011), which goes beyond disciplinary knowledge and is built around engineering design and problem solving, as demonstrated above. This view of engineering as practice is in line with the Threshold Learning Outcomes (Cameron & Hadgraft, 2010).

There are examples of curricula built around design and problem solving. Aalborg University in Denmark has practised this approach for 40 years, with a curriculum that is half project and half supporting modules (Kolmos, Fink, & Krogh, 2004). Students learn to do engineering from semester 1 by working in teams. The university even provides a room in which each team can work. Research has shown that the Aalborg graduates are better prepared for work than the graduates of the traditional universities in Denmark on most measures of performance (de Graaff & Kolmos, 2007). This approach was the inspiration for the engineering curriculum at Central Queensland University, where 50% of each semester is project work.

Other Australian Examples include Chemical Engineering at UQ (Crosthwaite, Cameron, & Lant, 2001) and Civil, Environmental, and Chemical Engineering programs at RMIT (Hadgraft, Xie, & Angeles, 2004). Many other engineering programs have also implemented more project-based learning.

Another, more recent example of a whole-of-curriculum approach, is Olin College in Boston, USA, where the curriculum was designed around doing rather than knowing (Buderi, 2014). Students get into action from day one and acquire knowledge as required, rather than be lectured at until they are considered to have enough knowledge to do something useful.

All of these example curricula have started with design and problem solving as the central activity of the curriculum, occupying typically 25-50% of each semester. These project courses can be used to systematically teach concepts and practices that would otherwise be taught in separate courses, e.g. communication, teamwork, self management, project management, ethics, sustainability, innovation and creativity, critical thinking, information management.

The remaining 50-75% of the curriculum is where the disciplinary knowledge is taught. This is enabling knowledge for engineering practice, e.g. fluid mechanics, thermodynamics, circuit theory, mass transfer. In the future, these enabling skills will be taught using self-paced adaptive learning tutorials. Although there will still be academic input on occasion, most students will progress through these tutorials without much help – likely, helped more often by their colleagues rather than by academic staff.

The real curriculum will be the projects and that's why they deserve to be 50% of the curriculum. This is where students learn to be engineers. This is where students value academic input. This is also where we can easily bring in industry adjuncts to work with the students. It's easy to have a practitioner come in and run a design class based on work they have recently done themselves. We are already seeing learning spaces reflect student-centred practice activity rather than teacher-centred lecture theatres and tutorial rooms.

These new curricula are the opportunity for the future – engineering curricula based around engineering practice. Students learn technical skills from online tutorials and practise and integrate them through realistic project work.

Conclusions

The paper has described a data driven approach to understanding the relationships between the 16 elements of the Stage 1 Competency Standard. Persistent clusters have been observed across the 17 academic participants. What is clear is that the design/project competencies are centrally connected (i.e. rated as 'proximate' by all participants) with all other competencies. This supports the PBL spine adopted by some universities, as described above. More data collection will shed light on the four competencies that seem less well aligned, namely, research, innovation, ethics and project management. The proximity data related to 'innovation', in particular, is ambiguous, requiring further clarification.

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