Focus Area 1
Working Group

A manifesto for programme design to capture the complexity of teaching and learning

Shaping the Future

iEarth

CENTRE FOR EXCELLENCE IN EDUCATION

Without a diversity of opinion, the discovery of truth is impossible
– Alexander von Humboldt

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Shaping the Future

This document outlines the rationale, objectives, and guiding principles of the Focus Area 1 project, aimed at fulfilling the iEarth vision and epitomised in our Manifesto statements.

The iEarth vision

To create a student-centred, innovative learning environment for future earth system scientists and citizens to meet complex societal challenges and opportunities. This will be done by promoting active learning and real-world problem solving through a nationally integrated earth system science education programme with a global perspective.

Earth system science – opportunities and challenges

The Sustainable Development Goals [2] underscore the fundamental human and societal importance of understanding the planet that sustains our civilisation. Traditionally, earth science has not been considered a 'core' science discipline, but this view is no longer tenable, as made all too clear by the wicked problem of climate change [16]. On the one hand, earth science has the advantage of being directly relevant to human lives and socioeconomic activities (Fig. 1).

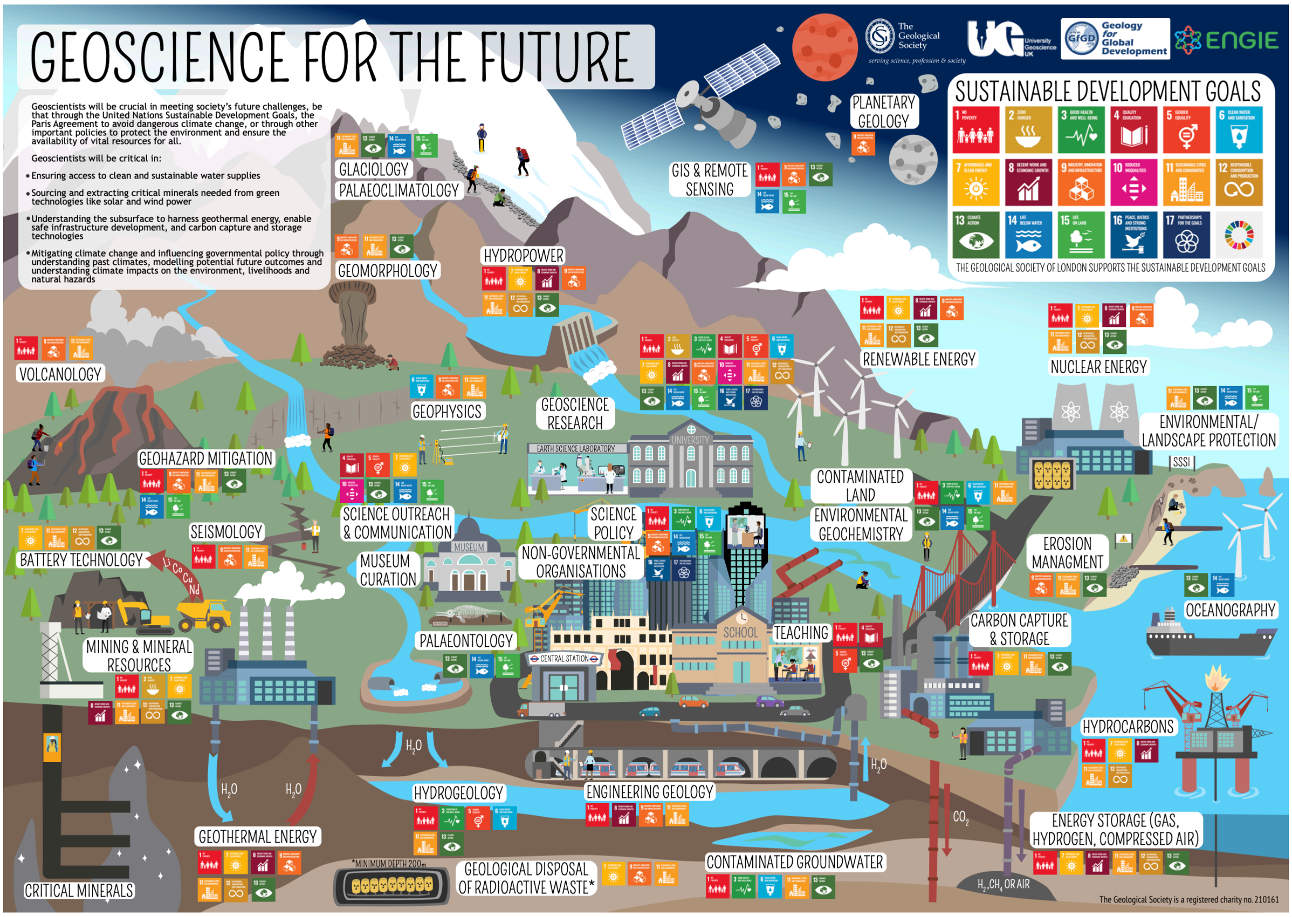

Figure 1: Geoscience competencies are critical for meeting the Sustainable Development Goals (Poster courtesy of the Geological Society of London).

On the other hand, the complexity of dynamical earth systems poses a formidable challenge for teachers and learners [1, 19, 21, 22]. We note that earth systems are not just complex in the sense of involving many components that are traditionally studied by separate research communities (Fig. 2), but also dynamically complex in a formal sense, involving far-from-equilibrium, non-linear, and non-autonomous dynamics [7]. These properties require systems-level learning.

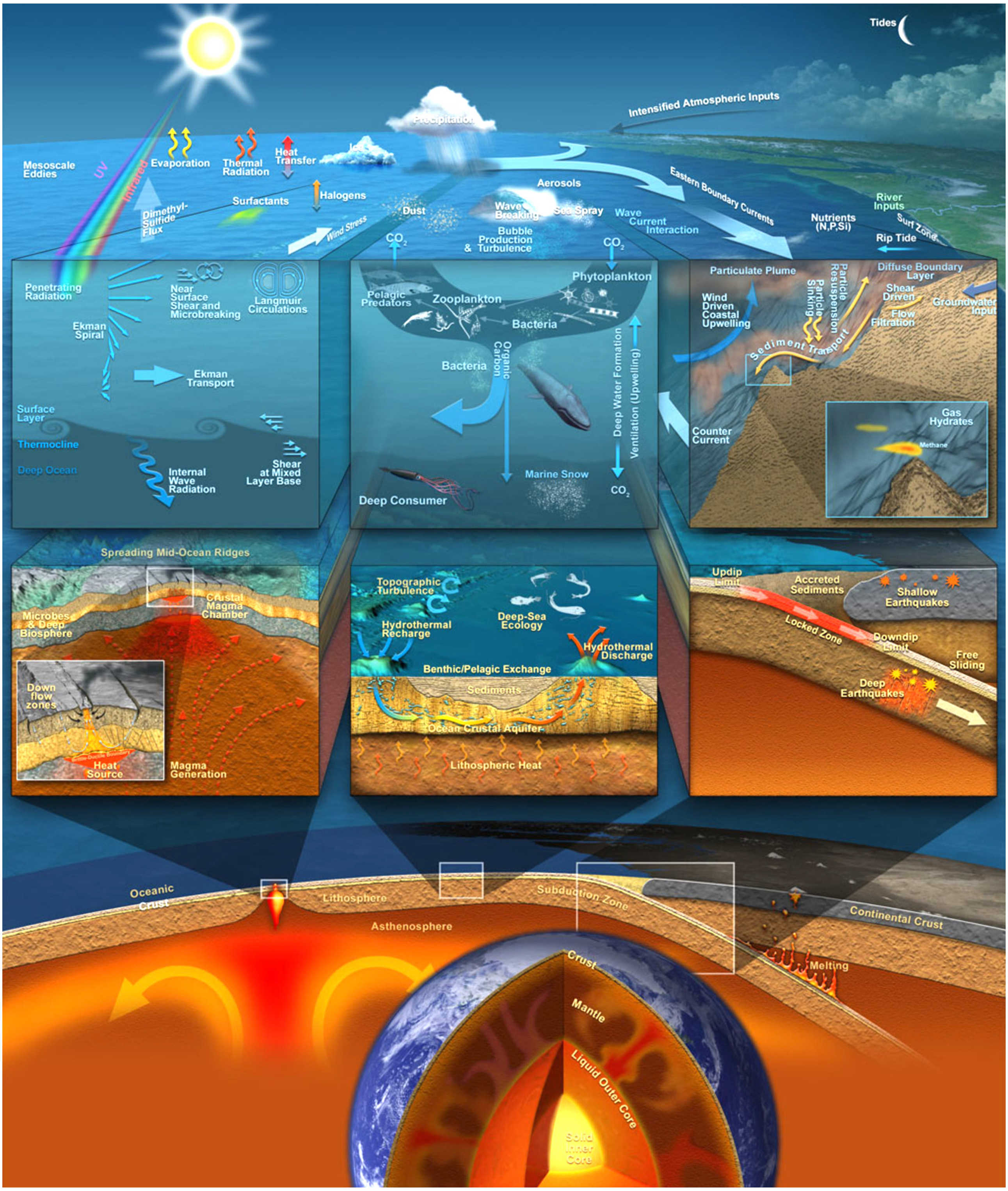

Figure 2: A systems perspective challenges the long tradition of disciplinary fragmentation (ocean science poster courtesy of University of Washington Center for Environmental Visualisation).

Like the medical sciences, earth sciences deal with a system of existential importance to human life and well-being. Traditional disciplinary labels (e.g. 'geology') fall short when faced with the interconnected web of phenomena that make up the earth system (e.g. the carbon cycle). To highlight what unites us as earth scientists and to counteract disciplinary fragmentation, iEarth flags five interconnected phenomena that are of existential importance regardless of how we might study them:

The GREEC pillars of iEarth

- ❑ *Geohazards*
- ❑ *Resources*
- ❑ *Energy*
- ❑ *Environment*
- ❑ *Climate*

Unlike medicine, however, earth science is not a licensed profession with certification standards. As a diverse community of active scientists, we have different perspectives on what earth science *is*, and we therefore have different perspectives on earth science education.

Implications for teaching and learning

As climate change has risen on the global agenda, there has been a shift towards a more integrated systems approach to earth science. But what does the rise of earth system science imply for higher education *teaching and learning*? To address this question, we lean on analyses of how students learn to work on real-world problems that involve complex earth systems and societal impacts [10, 12, 21] (Fig. 3). Unlike classic textbook problems that typically have solution recipes and a correct answer, working with realistic, ill-structured problems (in science, the workplace, or society at large), requires a different type of training [12]. Student-active learning in such real-world contexts mobilises a set of key scientific practices [17], and requires a supportive learning environment [9].

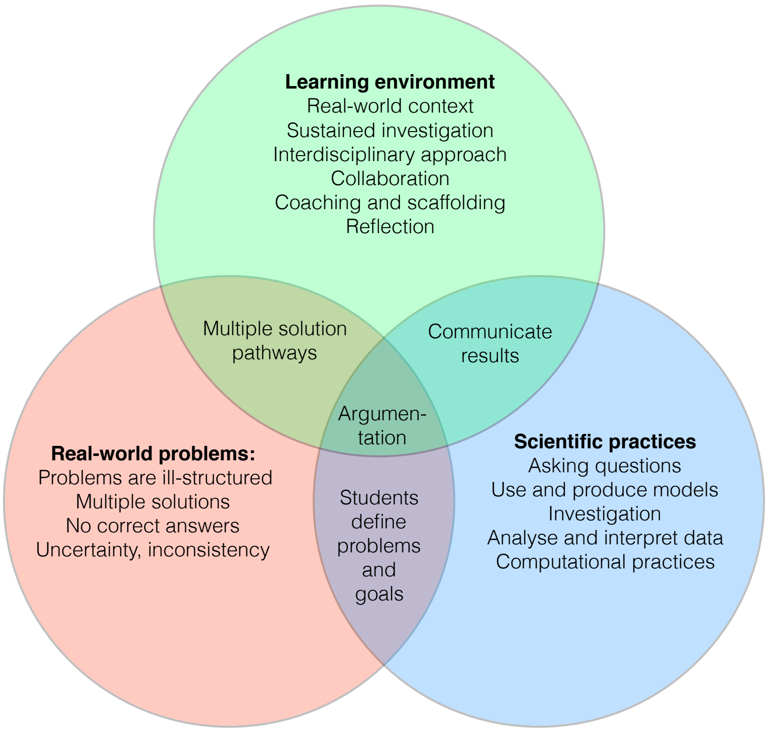

Figure 3: A framework for students to develop expertise in working with real-world issues involving complex earth systems [modified from the Problem Solving in Practice (PSP) model in Ref. 10].

Re-imagining the GEO programme

The Bachelor's programme at the UiB Department of Earth Science (GEO) is by some criteria a success. For example, we have the most satisfied students among the earth science programmes in Norway, according to the Studiebarometeret in 2020. In terms of programme-level structure and design, however, we are essentially limited to a list of courses, and it is difficult for students and staff to make sense of the programme as a whole*. Using the PSP framework (Fig. 3) as a lens, we can take a fresh look at teaching and learning activities in the GEO programme and recast them as instances of learning more general competencies relevant to both researcher training and to society at large.

GOAL

To re-imagine the bachelor's programme as an integrated network of learning activities that form coherent learning progressions.

Transcending the limitations of courses as units

Courses are the operational unit of education and completely dominate our thinking, design choices, and administration of teaching. This "course-graining" can obscure programme-level structure (Fig. 4A). Courses are named using unsystematic labels that have more to do with departmental politics than with educational principles. As a result, our perception of what *exists* in the educational programme is shaped by arbitrary labels that exaggerate divisiveness and prevent us from seeing commonalities and connections within the programme. To move forward, we instead need to focus on how student activities and assessments form an underlying "flow" of learning progressions (Fig. 4B) in terms of competencies and skills that allow for a multitude of labels to co-exist.

Figure 4: Shifting the focus from courses to programme structure. (A) Courses as discrete units obscure programme-level structure, even if some courses have similar labels. (B) Designing the programme as a network of learning activities that form meaningful progressions where students build relevant competencies. Courses are defined by a grid, but we focus on the underlying flow.

*Biggs [ref. 3, p. 68]: like sawing the branches off a tree, stacking them in a neat pile and saying, "There! See the tree?"

Capturing the complexity of teaching and learning

We highlight here some insights from the MERlin project, a competence-oriented curriculum[†] mapping across a consortium of German medical faculties [6, 15]: The prospect of labour-intensive curriculum mapping was met with strong resistance among staff, and some pilot departments refused to do mapping by means of enormous spreadsheets. A more user-friendly, web-based mapping tool was developed, which played a pivotal role in overcoming this resistance. Simple and intuitive visualisations of underlying curriculum data was a “door opener” that sparked interest in further analyses and mapping. We believe this is an important lesson, and that a well-designed ’app’ is needed to make the educational programme open and available to everyone.

GOAL

An online tool for everyone to explore, visualise, and collaborate on educational development.

However, we need a more flexible approach than the MERlin framework, which rested on a consensus catalogue of competencies using a relational database architecture [6]. To resist the external threat of standardisation in education, we need to uphold academic freedom, difference of opinion, and critical inquiry. Success in this project therefore depends critically on capturing multiple perspectives and meanings among the highly interconnected elements of teaching and learning (Fig. 5).

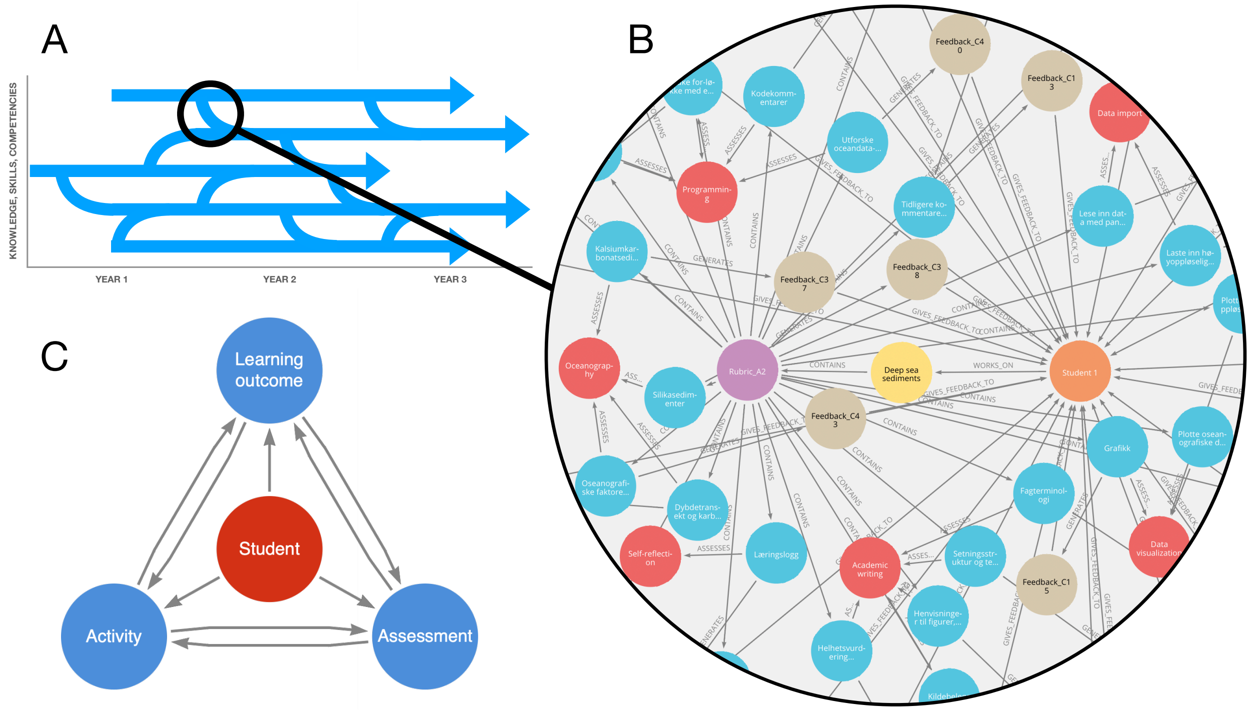

Figure 5: Capturing the complexity of teaching and learning. (A) The programme idealised as a web of interconnected learning progressions. (B) The underlying network consists of entities or *nodes* (e.g. students, activities, assessment criteria) and actions or *relationships* (e.g. working on tasks, giving and receiving feedback, self-reflection). (C) A simplified view of constructive alignment, which critically depends on the *relationships* between activity, assessment, and learning outcome [3].

[†]In the iEarth context of discipline-based higher education we use the term ’programme’ rather than ’curriculum’.

A graph database approach

Graphs are mathematical representations of a network (Fig. 6), and graph databases have become a popular tool for understanding complex systems in many domains [20]. In this project we will use the Neo4j platform. In graph databases, the connections between entities are as important as the entities themselves and are captured in a graph data model called an *ontology*. The term ontology is used in informatics to define a set of representational elements (classes, properties, and relationships) needed to model a knowledge domain or discourse [8]. Ontologies are more flexible than database schemas and better able to represent complex heterogeneous information, and they are widely used in life science data management (e.g. the Gene Ontology project).

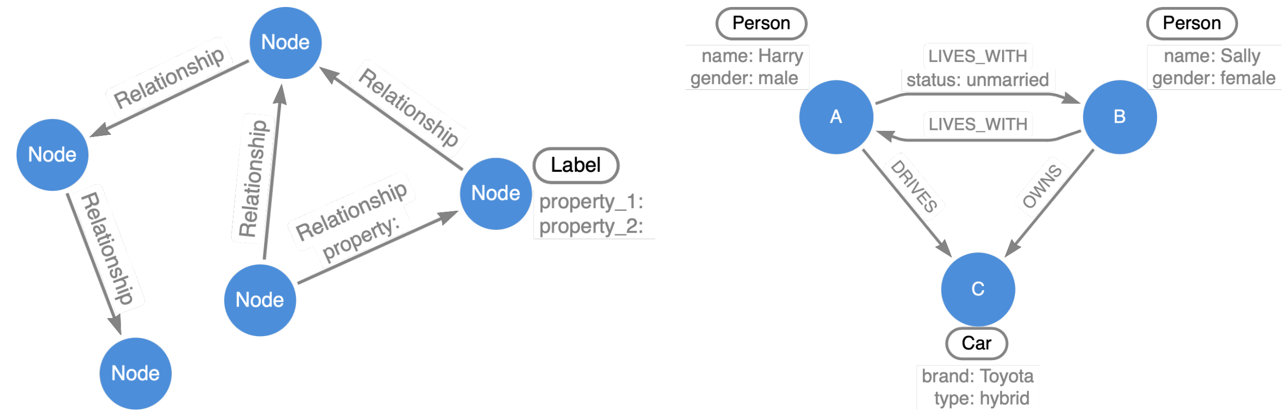

Figure 6: A graph is a representation of a network of entities (nodes, or vertices), and lines connecting them (relationships, links, or edges). In Neo4j, nodes and relationships can have multiple properties, and nodes can support multiple labels. Nodes can be thought of as nouns in sentences, and relationships as verbs that connect the nouns, e.g. person A lives with person B who owns a car, and person A drives a car that person B owns. Graph ontologies thus map intuitively to the real world and align with the questions we want to address. These graphs were made using the Arrows.app.

What are the questions we need to address?

A major advantage of graph databases is that the ontology (i.e. the representation of the knowledge domain) is flexible and can be adapted to the questions we need to answer and the analyses we want to perform. In our project, the graph ontology needs to support two mutually reinforcing processes: a design process and a mapping process, both of which are briefly outlined below.

In terms of programme design, we have already highlighted the need for increased transparency, and we want everyone involved in our education to be able to use the graph database to easily answer familiar yet currently intractable questions such as these:

TRANSPARENCY

- **STUDENT**: Why am I learning this?
- **TEACHER**: Do students already know this?
- **EMPLOYER**: What skills do graduates have?
- **INSTITUTION**: How is work load distributed?

Our ambitions go beyond programme design, however, because the graph database and application will enable us to address a much wider range of questions central to the iEarth change process.

Leveraging graph data science

The ability of graphs to capture complexity is not an end in itself but a prerequisite for building a database that underpins a programme visualisation, analysis and development framework. Graph algorithms allow us to analyse the structure of a network to answer questions and make predictions about how a system works or how entities behave within it [18]. These types of analyses (Fig. 7) are well-suited for the purposes of programme design and mapping. For example, we can use community detection algorithms to find groupings or partitioning within the programme structure; centrality algorithms to assess patterns of influence; similarity algorithms to identify redundancies, and pathfinding algorithms to analyse learning progressions.

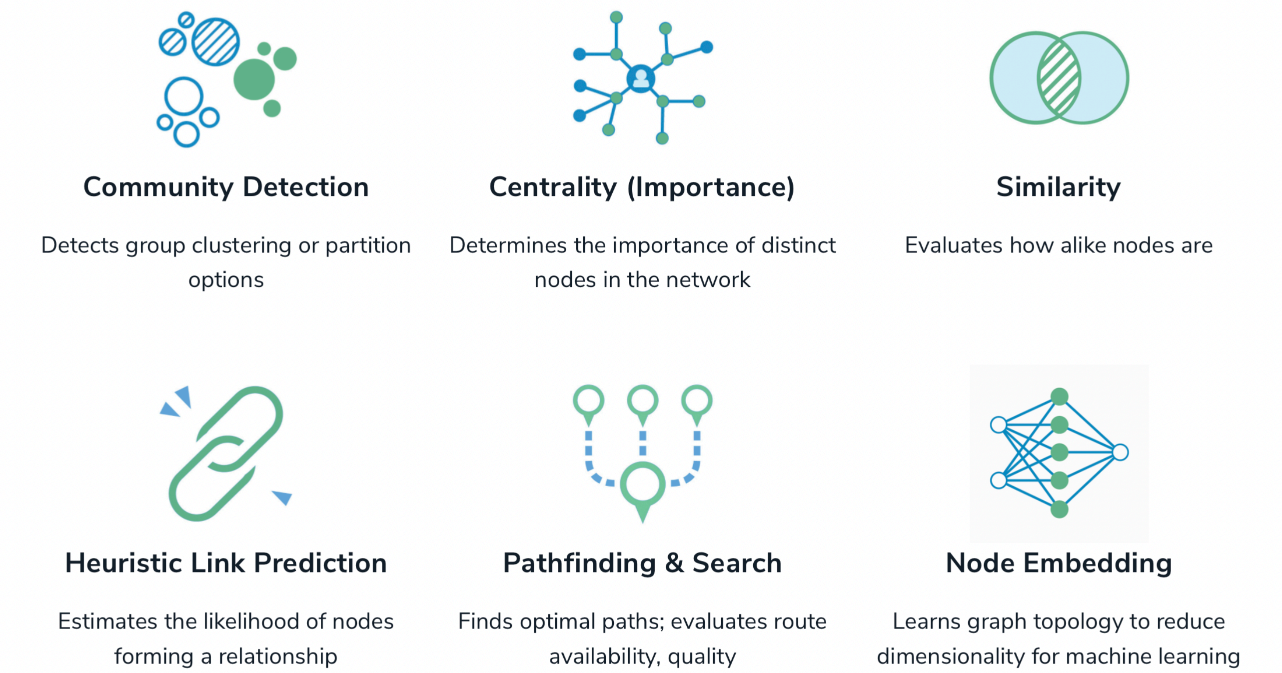

Figure 7: Examples of graph algorithms from the Neo4j Graph Data Science library.

The design process

One of the sparks that ignited this project is the work done by the UiB Learning Lab to develop a model for programme redesign, which is currently being tested at two other departments at UiB. This model is adapted from a Texas A&M curriculum redesign model that takes the form of an agile development cycle with elements from engineering design processes [5]. One of the key process steps in this model is to build a matrix of courses and outcomes and identify where programme learning outcomes are introduced, reinforced, strengthened, and demonstrated. This matrix approach is coarse-grained and assumes a high level of transparency, alignment and shared understanding.

Here we aim for a graph representation with much higher granularity and connectivity allowing us to more faithfully map and shape the educational landscape. We will achieve this by a bottom-up process of trial-and-error and negotiation resulting in an *ontology*: a set of agreed guidelines for how we represent the elements of teaching and learning in a graph data model as nodes, relationships, properties and labels (Fig. 6). We thus seek to create a shared sense of purpose and meaning (beyond the working group) in a community with different perspectives, constraints and priorities.

GOAL

Develop a graph ontology for teaching and learning that is robust enough to act as a shared representation, yet flexible enough to support multiple perspectives across earth sciences.

Although we support all initiatives to improve existing courses, our ambition is to design a new programme structure as a web of learning activities that form coherent learning progressions. After we had decided to use a graph database as a design framework, we were thrilled to find commonalities with the Cambridge Mathematics Framework (CMF) project, which ”*treats mathematics as a connected web of ideas in which different meanings can be found at different levels of organisation. This web is built in a graph database (Neo4j) [...]. A web-based platform [...] includes tools to search, filter and visualise [...] and view different levels and types of information as connected layers.*” [11].

The CMF offers a wealth of insights useful for our design process. We stress, however, that although we want to model teaching and learning activities in the form of graphs, we do not intend to build a full concept map for earth sciences. Rather than ask what a student should ”know”, we will focus on what a student should be able to *do*. Our graph ontology needs to act as a shared representation, starting with a meta-level taxonomy (e.g. the PSP model, Fig. 3) that enables us to connect different subject categories and sub-disciplines‡. Our ontology and the design process and methodology will be described in more detail in a forthcoming paper. Here we tentatively outline some of our proposed design principles:

Ideas for design principles

- *Build on research and critical inquiry*
- *Be participatory and collaborative*
- *Seek high granularity and connectivity*
- *Target student actions and motivating experiences*
- *Make connections via competencies and skills we share across disciplines*
- *Let elements of teaching and learning have multiple disciplinary labels*
- *Allow flexible learning trajectories*

We can illustrate our approach to programme design schematically in a simplified space with time along the first axis and the second axis representing a spectrum of learning descriptors or qualifications (Fig. 8). Here we exemplify this spectrum using the Norwegian National Qualifications Framework categories ’knowledge’, ’skills’, and ’competencies’, but we are by no means limited to shoehorning elements of teaching and learning into these categories. Instead, we can treat these three descriptors as examples of the interconnected layers of meaning that are embedded in the programme structure.

In Fig. 8A, each little “molecule” represents a learning activity with learning outcomes, tasks, and assessment. It involves a certain number of student work hours and an associated number of ECTS points. As a teacher, you are responsible for the quality and constructive alignment of outcomes, tasks and assessments in a learning activity. Activities are connected through common elements, which can be diverse and described in terms of disciplinary topics, generic skills, and transversal competencies. Furthermore, activities build on each other temporally in a meaningful way to form learning progressions. Clusters of connected activities can be blocked into modules or course units

‡For example, a single learning activity where students work on deep-sea sediments could support a multitude of labels, e.g. ’geochemistry’, ’geobiology’, ’oceanography’, ’geophysics’, ’marine geology’, ’sedimentology’, ’Quaternary geology’,...

based on work load and credits, depending on administrative needs (Fig. 8B). However, as a teacher you are not locked to a specific course in a specific semester, but free to use your expertise to work with students at different stages of the programme where your learning activities are most effective.

Because the elements of each learning activity can be associated with multiple labels, we can design, map, visualise and analyse the programme from many different perspectives (Fig. 8C). For example, we may trace student learning trajectories in terms of disciplinary topics (red; e.g. "geochemistry"), skills (green; e.g. "field mapping") or competencies (blue; e.g. "collaboration").

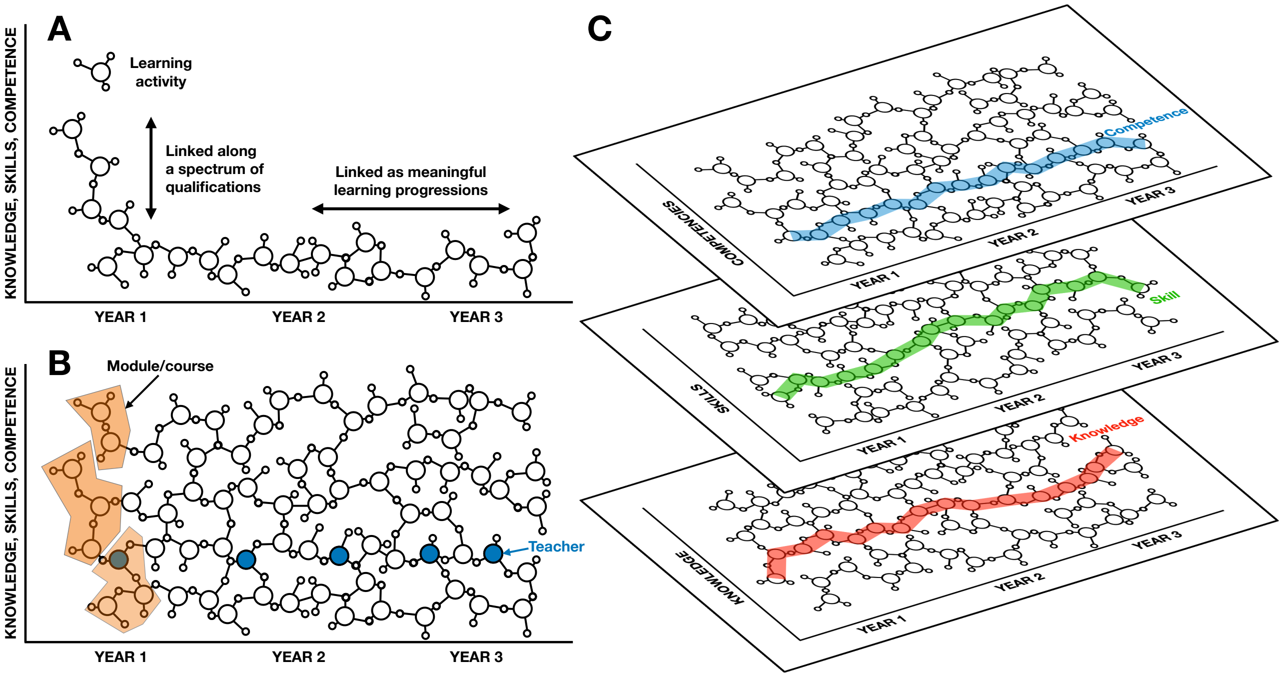

Figure 8: Schematic representation of the graph approach to programme design. (A) Learning activities are connected along a spectrum of qualifications and linked temporally into learning progressions. (B) Modules or courses emerge from the structure. Individual teachers can use their expertise to do activities and assessments where they are most effective (e.g. blue dots). (C) The programme can be analysed from multiple perspectives, here exemplified by the three qualifications categories. Note that the layers are densely interconnected but each layer is a unique representation and the coloured trajectories can be independent of each other.

The mapping process

It is important to stress that our criticism of a course-based focus refers to a lack of transparency and alignment at the programme level (Fig. 4), and is by no means a criticism of the quality of teaching and learning taking place in existing courses. On the contrary, there are many elements within the GEO programme that we believe are of outstanding value.

In the process of designing a new programme we therefore need to also engage in a careful mapping and analysis of the existing programme. These two processes are meant to reinforce each other, in the sense that the graph ontology helps define the entities and actions we need to map, and the mapping of the existing teaching and learning activities helps us identify some of the building blocks and connections needed to shape the future educational landscape.

GOAL

Map the elements of teaching and learning within the existing programme using the graph ontology to enable transparency and alignment in a new programme structure.

Graph databases can be used to create maps of the existing programme by extracting course information directly from the institution's web pages or learning management systems (see, for example, the MIT mapping lab). This approach to mapping with graphs intersects with the field of learning analytics, which makes sophisticated use of network analysis [4].

Our aim is not to infer graphs from big data, however, but to engage our colleagues in a qualitative process to make sense of the educational programme. Our approach is to invite instructors and students to the working group to learn about their educational goals and priorities, collaborate on how to "graph" what goes on in their teaching, and discuss how their expertise can be integrated in programme-level learning progressions. In order to support the programme design process, we again wish to shift the focus away from "privately owned courses" towards connected activities and assessments that build relevant competencies. As we move forward we will describe the mapping process in more detail.

A note on change theories

The iEarth project is a change initiative, and research on change in higher education shows that such initiatives are more likely to succeed if they are informed by and can leverage multiple theories of change [13]. For example, in a recent STEM education change initiative in the US featuring some similarities with the Norwegian Centres of Excellence in Education instrument, change agents used Systems Theory and Institutional Theory to understand external top-down forces and interconnections across institutions, and they used Organisational Learning Theory and Network Theory to understand knowledge management, sharing, and diffusion of change through networks [14]. The iEarth FA1 project outlined in this document is also the topic of a PhD project that will use elements of Network Theory, including social network analysis and diffusion of innovation, to investigate the change process. A more detailed account of change theories and how they inform our strategy will be provided in a forthcoming paper.

Manifesto

- We uphold the fundamental importance and urgency of understanding the planet that sustains human existence. A research-based, transparent, and forward-looking earth science education is essential for meeting future societal challenges.

- We treat earth science education as an evolving ecosystem of concepts and competencies that can adapt to new insights and needs. Students, teachers, institutions, employers, and policy makers all need to make sense of the educational programme from different perspectives.

- We represent the educational programme as a network of entities and actions, and build a graph database that captures the complexity of teaching and learning. The graph ontology is negotiated through a collaborative, bottom-up process of discussion and analysis. This shared representation supports programme design, mapping, and research.

- We develop a web-based application tailored to user needs with tools to explore, visualise, and collaborate on shaping the future of earth science education. This framework will foster more and better conversations about teaching and learning, and enable community engagement, dissemination and evaluation of the educational change process.

- We learn from research on design processes and change initiatives in higher education and use these insights to inform our strategy and to analyse, adapt, and adjust the change process as it unfolds.

About the working group

The following list represents the first instalment of the iEarth Focus Area 1 working group. This pilot group includes two students and six academic staff members from the University of Bergen Department of Earth Science (UiB GEO), two PhD candidates in educational research, a member of the UiB central study administration, a member of the UiB Learning Lab, and an iEarth visiting professor from Lund University, Sweden.

Erle Birkeland is a MSc student in the UiB GEO programme and the Center for Deep Sea Research, working on ore-forming processes in volcanic systems at the Arctic Mid-Ocean Ridge. She is a supervisor for the Student Mentor Programme.

Dario Blumenschein is an iEarth PhD candidate at the UiB GEO with a background in educational sciences and pedagogy. His research focusses on higher education change processes and topics of teaching and learning.

Andreas Born simulates climate and glaciers using numerical models. His motivation stems in equal parts from the elegance of physics, the power of modern computers, and the mysteries of our planet's past.

Isabela Darcie is a PhD candidate at the UiB Department of Education investigating formative assessment and student engagement in active learning environments in Higher Education. Her research interests also include course design, student and instructor experiences, and cognitive sciences.

Christian Haug Eide is an associate professor of sedimentology at UiB GEO. His research, teaching and supervision focuses on how sedimentary deposits influences subsurface reservoirs, landslides, anchors for offshore wind and magma transport through the crust.

Bjarte Hannisdal is an earth scientist whose research interests include quantitative geobiology and causality in dynamical systems. He is the iEarth Education Chair at UiB GEO and the leader of iEarth Focus Area 1.

Kari Bjørgo Johnsen is involved in educational development as a senior adviser at the UiB Learning Lab. She enjoys being involved in the design and redesign of courses and programmes, with an emphasis on what the students do. She views development work in higher education as cultural work that depends on the joint efforts of academic staff, students, educational leaders and technical-administrative staff.

Henk Keers is an Associate Professor in geophysics at UiB GEO. He has been teaching a number of courses in geophysics, with emphasis on computational geophysics and he was recently promoted to Excellent Teaching Practitioner.

Alan Kvindesland is a MSc student in the UiB GEO programme. He works on reconstructing sea surface temperatures off the East coast of South Africa during the last glacial cycle using the clumped isotope method.

Henriette Linge is an earth scientist doing research and teaching in surface processes and geochronology. She is the scientific manager of UiB's Cosmogenic Nuclide Preparation Facility, holds an adjunct position at the University Centre in Svalbard, and she is an Excellent Teaching Practitioner.

Desiree Roerdink is an Associate professor in Analytical geochemistry at UiB GEO. She has developed and is teaching courses in mineralogy, geobiology, isotope and analytical geochemistry.

Torgny Roxå has worked in educational development for 34 years, mainly on wide change through a cultural approach. He has extensive experience from training change agents and inspiring various initiatives like rewarding teachers and student evaluation of teaching.

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