PILLARS AND LINTELS: THE WHAT'S, WHY'S AND HOW'S OF INTERDISCIPLINARY LEARNING IN STEM EDUCATION

Summary

Interdisciplinary learning (IDL), one of the four contexts for learning of Curriculum for Excellence (CfE), cannot be properly understood without a clear understanding of the nature, benefits and limitations of disciplines. Disciplines are branches of learning characterised by distinct objects, concepts, principles, theories, skills, tools and applications, and comprise groupings of 'like-minded' people. By ensuring depth of knowledge and understanding, disciplines give rigour and structure to the development of knowledge and importantly are characterised by their transferability and applicability to other areas of knowledge.

Science disciplines may also be inward-looking and fail to address new and relevant real-world problems, whereas major new insights and breakthroughs increasingly occur in interdisciplinary areas. In IDL learners draw on two or more disciplines in order to advance understanding of a subject or problem that extends beyond the scope of any single discipline. Successful IDL must provide substantial disciplinary knowledge and understanding that is also transferable into different contexts. By contrast, multi-disciplinary learning involves the juxtaposition of disciplines and knowledge that may have no apparent connection and may be taught as separate entities around a theme or topic. Successful development and delivery of IDL in STEM will require a strong and sustained external support system to provide CPD and support development of learning communities.

Rapid scientific and technical innovation has irreversibly altered the demand for skills in a hyper-connected global marketplace. Employment growth will continue to favour highly-skilled and tertiary-educated workers. Skills are the global currency of the 21st century in which working life will become even more networked. Work will be increasingly variable and done on a project basis in collaboration with various contributors with complementary skills working in teams. These skills require practice through change of teaching and classroom practice and should be developed at all levels throughout education. This implies a shift to higher level inter- and multi-disciplinary knowledge and training.

The successful delivery of IDL in Scottish secondary schools with timetables designed around individual disciplines and disciplinary thinking is a major challenge in CfE. In primary schools one teacher will teach most if not all subject disciplines but with limited disciplinary knowledge. In secondary schools, two common approaches to IDL are emerging in school-timetabled IDL; these are large-scale events for large groups (e.g. entire year groups) and classroom–based IDL, setting aside time for multiple disciplines to allow pupils to work on IDL projects within their normal daily timetable. The support of STEM teaching in IDL contexts in primary schools, where few teachers have formal STEM training, is particularly critical. These and other models, together with STEM teaching in IDL contexts in primary schools where few teachers have formal STEM training, require well-structured and sustainable support from HEIs through development of professional learning communities.

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Interdisciplinary learning (IDL) has been adopted as an essential context for learning of the *Curriculum for Excellence (CfE)*. With its focus on relevant themes or problems, IDL has the potential to enhance the development of all four capacities of Curriculum for Excellence: successful learners, confident individuals, effective contributors and responsible citizens. But what exactly is IDL, what benefits for Scotland's future economy and society will emerge from its implementation in CfE, and how will it be delivered in practice? The principles of IDL that are reviewed here in relation to STEM (Science, Technology Engineering and Mathematics) subjects should also find wider application and relevance beyond the STEM disciplines.

1. What is Interdisciplinary Learning? View from the world of education and training

<u>Disciplines</u>

In order to understand the ***nature*** and ***principles*** of **interdisciplinary learning**, we require a clear understanding of the characteristics and importance of **disciplines**, and their benefits and limitations. Disciplines as a means of structuring academic and educational practice have been well established in UK education at all levels for over a century. A discipline is a branch of learning or domain of knowledge that is characterised by distinct objects, concepts, principles, theories, skills, tools and applications. Established disciplines, in schools, colleges, and higher education and research institutions alike, comprise groupings of 'like-minded' people with a shared language who subscribe to their principles and methods, interact with each other, and communicate and apply their knowledge and understanding in society, for example through education, research and economic activity. Although disciplines may be resistant to externally imposed change, they are continuously evolving and developing from within as knowledge and understanding increase, especially in the STEM subjects. Thus their boundaries are not fixed and cannot always be easily defined. The accumulation of knowledge within science disciplines leads to increasing internal specialisation and division.

Disciplines give **structure** and **rigour** to the development of knowledge, and are vital to sustaining and curating that knowledge and communicating it to non-experts and to future generations. Disciplines provide a reservoir of knowledge and skills that have value in society and confer benefits to economies. STEM disciplines are characterised by their **structure** - concepts, principles, theories and methods - from which detailed outcomes arise, predictions are made and theories tested. The more fundamental the idea or skill that has been learned, the greater should be the breadth of its **applicability** to problems and its **transferability** to other domains of learning and disciplines. By contrast, if learning comprises unconnected knowledge, information or skills that are not placed within - or related to - a structured framework (such as science disciplines) they are likely to be rapidly forgotten. Good teaching should impart an understanding of the underlying structure of a subject rather than simply a mastery of facts and techniques.

There are however also persuasive arguments against disciplines. The consistent focus on a single set of disciplinary phenomena may result in a lack of creative engagement with other disciplines and with the gaps between disciplines. Disciplines may be inward-looking and fail to address relevant, real-world problems. Learners may find it difficult to make links between disciplines. Disciplinary communities guard their boundaries in competition with other disciplines, yet it is in the gaps beyond disciplinary boundaries - the **interdisciplinary areas** - that major new insights and research breakthroughs occur.

<u>Interdisciplinary Learning</u>

The terminology used to describe IDL is varied and confusing. The terminology adopted here draws on work of Chettiparamb (2007) and Harvie (2012). In **interdisciplinary learning** learners **draw on two or more disciplines** in order to advance their understanding of a subject or problem that extends beyond the scope of any single discipline. Learners integrate and develop information, concepts, methodologies and procedures from two or more disciplines to gain new knowledge, understanding and skills, and commonly also to explain or solve problems. **Contextual learning** is an important and widely used type of interdisciplinary learning where different disciplines or curriculum areas are focused - or converge - on a context, issue or problem. Contexts are typically practical, real-world problems or issues, such as for example climate change or energy. When the disciplines are in different curriculum areas, for example sciences and social subjects, this is often described as **cross-curricular** learning.

By contrast, **multidisciplinary learning** describes the **juxtaposition of disciplines** which may have no apparent connection or may be taught as separate entities by one teacher but related to a particular theme or topic. Merely linking or juxtaposing discrete subjects together around a theme such as climate change is not by itself interdisciplinary (as defined above), but rather multidisciplinary. In good IDL, learners tackle relevant and meaningful questions or problems that will allow them not simply to make connections between two or more disciplines but also to **draw on and develop their disciplinary knowledge, understanding and skills** and thereby deepen their understanding of these disciplines. Only in this way will IDL enable and enhance the vital capacity to **transfer** and **apply** disciplinary knowledge, understanding and skills to new problems and into other areas of learning. While multi-disciplinary learning is not in itself a bad thing, it may fail to convey this transferable and applicable disciplinary knowledge and understanding.

IDL cannot exist separately from disciplines but is in practice fundamentally **founded on strong disciplinary knowledge, understanding and skills**. Furthermore, teaching specific topics or skills without clarifying their relationship to broader and more fundamental principles (starting from the specific rather than the general) makes it difficult for learners to transfer and generalise their learning to make it useable beyond the situation in which the learning occurred. Students undertaking IDL also obtain a deeper understanding of the links between disciplines and the transfer of learning.

<u>Interdisciplinary learning – the pros and cons</u>

Successful interdisciplinary learning has largely developed in higher education from *within* science disciplines in response to the recognition that major advances in scientific research typically occur at and between the disciplinary interfaces, where progress depends on making interdisciplinary connections and gaining new insights. This requires **teamwork and collaboration** amongst people from two or more disciplines, a practice common in industry and the workplace. There is a widely-held view that STEM education should reflect such practice.

The practice of IDL in STEM subjects creates and develops **awareness of wider career opportunities** and stimulates **curiosity and motivation**, while emphasising the inter-relationships of phenomena. In STEM education, there is a perceived need to stimulate the **prior interest** of learners in the material to be learned by emphasising its relevance to practical everyday problems, many of which require interdisciplinary approaches. If learners are interested in a problem they will become interested in the underlying science. Importantly, IDL also promotes **higher-order thinking skills** such as creativity, critical and systems thinking, synthesis, evaluation and analysis, and is commonly associated with diverse types of learning such as **co-operative, inquiry-based and contextual learning** (e.g. Harvie 2012). In implementing problem-based IDL, teachers become facilitators, supporting pupils to become self-directed learners.

The benefits that interdisciplinary and cross-curricular learning confer on learners within and beyond the STEM disciplines have been widely recognised and welcomed, but research evidence for the effectiveness of IDL in school education is as yet limited. Hurley (2001) has shown show that student achievement in science was greatest when maths was used in integration with science or to enhance science, and in maths when taught in sequence with science (i.e. planned together but taught separately). Riechert and Post (2010) showed that enrichment activities involving IDL work have positive effects on learners' interest in and attitudes to STEM. There is little evidence of interdisciplinary STEM in education systems in countries with a heavy reliance on individual subject examination, whereas countries that encourage a broader range of subjects post-16 including maths or science also tend to get higher participation rates in STEM.

Pillars and lintels – a balanced perspective

While strongly supporting the intention of CfE to develop IDL, the SEEAG Report (2012) concluded that '*Interdisciplinary working requires that all science subjects should continue to be founded on deep and coherent pillars of knowledge and understanding. Interdisciplinary understanding will lack rigour and utility if it is not part of a structure in which the disciplines are pillars with interdisciplinary work as lintels. Without the pillars, the lintels will fall'*. In other words, to be of long-term value the delivery of interdisciplinary learning must at the same time provide substantial rigorous disciplinary knowledge and understanding that are transferable into different contexts. How this balance is to be achieved in practice is one of the grand challenges of CfE.

Successful development and delivery of IDL within CfE is strongly dependent on teacher skills, a deep understanding of the *nature* of IDL and its relation to the STEM disciplines, a sufficient breadth and depth of subject knowledge, understanding and skills, and expertise in curriculum design. Practical logistical issues for schools (discussed below) include timetabling, cost, time and working with other departments. All these challenges will require a high and sustained level of support through CPD, development of professional learning communities (PLCs), reform of initial teacher education (ITE) and much more ongoing collaboration and engagement between schools, local authorities, universities and colleges, industry and other agencies. In other words, **change needs to be systemic**. Teachers need the time to think, plan and develop IDL. By tackling these challenges through the creation of strong, interconnected support systems and the establishment of creative partnerships, a roadmap can be created to enable Scotland to be a world leader in interdisciplinary learning.

2. Why is IDL important? View from the world of work

Pupils and their parents, teachers and employers, taxpayers and other stakeholders will all wish to be convinced about the economic, social and cultural benefits that this new emphasis on IDL within CfE will bring to young people. Will their employment prospects be enhanced and life experiences enriched? Will IDL implementation help to stimulate creativity, curiosity and enterprise, make Scotland more economically competitive and bring wider social benefits?

Fundamental shifts in the nature and structure of employment in developed countries have led to a decline in agriculture and manufacturing and growth in services. In manufacturing there has been a shift to development and production of high value goods. The number of higher skilled professional, technical and managerial jobs has risen at the expense of low-skilled employment. Rapid scientific and technical innovation have been the principal drivers of change in a hyper-connected global marketplace in trade, supply, finance, information, skills and knowledge exchange, generating widespread benefits through improved living standards but also greater complexity across economic systems, and with it economic, social and environmental vulnerabilities and potential for loss of competitiveness. These changes have irreversibly altered the demand for skills, with a shift away from routine cognitive and craft skills and physical labour. Scotland must now compete in international marketplaces on an entirely different basis, with leading emerging economies poised to overtake that of the developed OECD economies through more rapid growth.

Employment growth will continue to favour highly skilled (tertiary-educated) workers. The boundaries between manufacturing and service sectors will blur and greener technologies and practices will diffuse across economies. Long-standing structural weaknesses in the UK economy reflect years of inadequate investment in skills, infrastructure and innovation, with a long post-industrial legacy of educational and social inequity. If the UK could raise educational standards to those of leaders such as Finland it could add more than £8trn to GDP over the lifetime of a child born today, equivalent to one percentage point on annual growth (CBI). Improving the quality of school education is a key growth and investment issue. The widely-sought social dividend that improvements in human capital achieved through raising educational performance nationally directly addresses the enduring challenge of educational, economic and social inequity.

This is the world in which we now live and work. What are the implications for education and skills in general and for STEM education in particular? Skills have become the global currency of the 21st century and are the key to translating innovation, curiosity and creativity into economic growth and employment. Emerging economies have made substantial long-term investment plans for education and skills development. By contrast, for developed economies with ageing demographics such as Scotland the need to ensure that their human capital keeps pace with rapidly evolving skills demands of labour markets is particularly acute. Working life in 2020 will be even more networked, and jobs less routine. Work will increasingly be done on a project basis in collaboration with various contributors with complementary skills, and tasks will become more variable. An ability to apply network skills is the foundation of future work, and network skills find their application in the ability to find, use, connect and disseminate knowledge, to identify new opportunities and find solutions to problems. Many of the most commercially significant innovations in industry are expected to result from cross-disciplinary fertilisation. The key to success is the ability of people with different competences to work together in teams, learning from one another and building on existing ideas. These are skills that require practice, require development of both curriculum and teaching/classroom practice, and that should be developed throughout education at all levels through what we teach and how we teach it.

An OECD report identified the following key elements as essential in 21st century education systems in relation to skills and employment:

Knowledge:- relevance, real-world experience, rethinking of the significance and applicability of what is taught to strike a far better balance between the conceptual and the practical.

Skills: - higher-order skills, such as creativity, critical thinking, communication and collaboration are essential for absorbing knowledge as well as for work performance, requiring expertise in combining knowledge and skills in a coherent ensemble.

Character (behaviours, attitudes, values): to face an increasingly complex world it is important to teach character traits, such as performance-related traits (adaptability, persistence, resilience) and moral-related traits (integrity, justice, empathy, ethics).

Demand for **STEM skills** is high, both within STEM-based industries and businesses and beyond. Many growth sectors are STEM based, with a high projected demand for *both* high-level STEM skills and more generic skills. Two thirds of businesses responding to a recent SCDI/Skills Development Scotland (SDS) survey identified the need for a greater focus on STEM subjects across the education and training system, emphasising leadership, planning and organising, team work, strategic management, technical and practical skills, advanced IT and software skills, plus improved written and oral communication skills.

The characteristics of good IDL coupled to modern classroom practice within CfE map remarkably well and very naturally onto the economic, employment, social and cultural environment of the 21st century. A new and higher-level inter- and multi-disciplinary knowledge base will be essential, with a shift away from narrowly focused specialists to flexible individuals with interdisciplinary academic training. In key areas such as STEM-related subjects there is a more general emerging skills need for interdisciplinarity within the science, technical and business areas, for which teachers will need to be able to combine approaches to teaching, work collaboratively internally and externally, and acquire strong technology skills. Specifically:

- Businesses will require young people with flexible skills and the ability to innovate and cope with change and learn continuously throughout life; knowledge transfer is as much about communication as specialist skills.
- Schools must stimulate a child's ability to solve new, non-routine problems, combine different bodies of knowledge and interact productively with others, which is essential if individuals are to become competitive in the globalised economy.
- Active learning based on student participation, experiential learning models and learn-by-doing approaches will matter more than passive approaches.
- Core skills should be delivered in a way which excites and engages learners.
- Skills development is more effective if the world of learning and the world of work are linked. Learning which incorporates business-related case studies and simulations and learning in the workplace allows young people to develop "hard" skills and "soft" skills, with real-world relevance and experience. It is apparent through SCDI's network of Young Engineers and Science Clubs that industry-set school challenges from a range of sectors are usually designed to require teamwork and an interdisciplinary approach.
- In STEM, students should be encouraged to run their own experiments, involving more open-ended questions and more organised group activity.

Feedback from SCDI members in STEM-related sectors supports IDL, but businesses require more definition of what IDL means if it is to be made meaningful. Bad IDL is seen as probably worse than no IDL. Good IDL needs to be respected by teachers, students, and employers. It should be exciting, but the teaching of core skills must not be lost. IDL should not involve random subject collaborations dictated by a pre-existing timetable, but rather good IDL requires faculty ownership, identifiable budgets, timetable priority, preparation and assessment.

3. How can IDL be delivered? View from the classroom

In Scottish secondary schools timetable structures are designed around individual disciplines and therefore are not 'naturally' designed for delivery of IDL. By contrast in primary schools one teacher will typically teach most if not all subject disciplines within CfE. In secondary education the challenges are therefore largely logistical in nature and related to delivery whereas in primary education the challenges are around identification, establishment and maintenance of a level of disciplinary rigour in IDL. Some good illustrative examples of IDL that embody the principles of IDL outlined above are highlighted below.

So how are secondary schools delivering project/challenge based IDL? Two common approaches appear to be emerging in school-timetable based IDL, while STEM clubs (or Young Engineers and Science Clubs) provide additional projects and challenges for pupils that are set in a real life STEM context and draw on several STEM disciplines as well as non-STEM disciplines (i.e. cross-disciplinary). Here reference is only made to school-timetable based work. However the high quality of many STEM club projects or challenges is evident and teachers may wish to look at the SCDI Young Engineers and Science Clubs website for examples and further information. Support is also available from STEMNET, through for example the STEM ambassador programme. A few schools opt for a mix of approaches to IDL and no one method should be seen as perfect.

1. Large scale events

In full-day IDL events a School will arrange for an entire year group to be out of class at the same time. The group will be set a task or project which has an IDL theme. Pupils will then work in a hall or with specific subjects throughout the day in order to complete their project. This could for example be a 'Murder Mystery' style forensic activity or a natural disaster aid mission. The benefit of such work is the experience for the pupil, and the prospect of being out of class for a day in a new working environment is clearly appealing to pupils.

Some points to consider for this method are: How is disciplinary rigour maintained? How will you ensure that pupils recognise the contribution of each discipline to the overall project or challenge? Does this project relate to career opportunities and skills required for the future? Can the event be sustained in the longer term and thus be adapted and developed year on year to fine-tune improvements (particularly if the event involves external partners)? Does an event of this scale allow personalisation and choice as well as differentiated support for pupils?

2. Classroom based IDL

In classroom-based IDL, management within a school will 'set aside' time for multiple disciplines to allow pupils to work on IDL projects within their normal daily timetable. To achieve this, several departments will develop an IDL project or challenge and determine how much time 'off timetable' (i.e. outwith their usual CfE lessons) subject disciplines require to spend on the work. Alternatively a school may decide to select an existing STEM challenge, for example to take part in the Junior Saltire competition. This would require lessons to be developed and delivered in a variety of subjects including for example science, CDT, computing, English and maths, with the teachers selecting a 'lead' subject that which will launch the project/challenge at the start and pull together the project at the end. There are clear advantages to this model in that it allows greater opportunities for differentiation, learners recognise each distinctive disciplinary contribution to the overall project, learners can identify areas of the curriculum where they are succeeding or require improvement, and teachers can ensure and assess individual discipline work based on prior learning as well as contribution to overall project based on well defined success criteria. When organised and in place there is less impact on the normal school day and the project can be run year on year.

Some points to consider with classroom-based models are: How much development time will be required by teachers to ensure each discipline is ready? Which will be the lead discipline? Would it benefit learners to launch the project during an assembly? How much time and space will be needed to bring the project together at the end so that pupils can showcase their work? What will be the success criteria at the start of the project and how will this be embedded with relevant skills and CfE Curriculum experiences and outcomes? How can the project be developed to ensure that pupils can be creative (see Blooms Taxonomy)?

4. Some illustrative examples of good IDL for primary and secondary (to be completed)

A. *Carbon Capture and Storage*. (Scottish Earth Science Education Forum (SESEF) and Scottish Council for Development and Industry (SCDI) level 3 Workshops)

- Topical inter-disciplinary investigation of the science and technology underpinning the generation, transport and underground storage of carbon dioxide, and the rationale in relation to climate change.
- Hands-on co-operative learning involving investigative role-play, leading to the construction of a miniature working carbon dioxide storage facility.
- Disciplinary science and technology elements include combustion, properties of carbon dioxide, behaviour of gases at high pressure (Boyle's Law), properties of rocks (porosities), effects of carbon dioxide on aquatic life (pH), power generation (generators and turbines).
- Incorporates numeracy and literacy elements and is supported by animations.
- Delivered and evaluated in several different models and contexts, including teacher CPD, classroom delivery in secondary schools with cascading to feeder primaries, and

pupil-led events at Edinburgh International Science Festival. Currently (2013-14) licensed for delivery across Scotland to Young Engineers and Science Clubs by SCDI.
- Funded by industry (Scottish Power, OPITO, Shell) and Scottish Government.

(other evaluated examples to be added)

Conclusions

A long-term national partnership programme is being established to support the development and implementation of IDL as a fundamental practice in Scottish education. Scotland's national educational organisations, the Scottish Government and ADES are working in collaboration with a range of external support groups, including STEMEC, the RSE Learned Societies group for Science Education, universities and industry, teaching unions and parent groups to support teachers and thus improve young people's learning experiences and help them to develop the STEM skills they will need in their further training and careers. Successful reform of learning, teaching, curriculum and assessment that includes IDL as a context for learning requires vision and systemic change, and this occurs only on decadal timescales.

References

This review paper draws extensively on the work of Bruner (1977), Chettiparamb (2007), Harvie (2012), Kline (1995) and the SEEAG Report (2012).

Bruner, J (1977) *The Process of Education*. Harvard University Press.
Chettiparamb A (2007). *Interdisciplinarity: a literature review*. The Higher Education Academy (www.heacademy.ac.uk/ourwork/networks/itlg)
CBI, *First steps: A new approach for our schools* (2012)
Education Scotland (2012) *CfE Briefing: Interdisciplinary Learning*.
http://www.educationscotland.gov.uk/Images/IDLBriefing_tcm4-732285.pdf
Education Scotland (2013) *The Sciences 3-18. September 2013 Update*.
http://www.educationscotland.gov.uk/Images/Sciences3to182013Update_tcm4-817013.pdf
Graham, CM (2014) *On Disciplines and Interdisciplinary Learning*.
http://www.scotland.gov.uk/Topics/Education/Schools/curriculum/ACE?Sciences/STEMEC/STEMECPapers
Harvie, J (2012) *Interdisciplinary education and co-operative learning: perfect shipmates to sail against the rising tide of 'learnification'*. Stirling International Journal of Postgraduate Research 1.1.
Hurley, MM (2001) Reviewing integrated science and mathematics: the search for evidence and definitions from new perspectives. School Science and Mathematics 101, 259-268.
Kline, SJ (1995) *Conceptual Foundations for Multidisciplinary Thinking*. Stanford University Press, Stanford, California.
OECD, *Better Skills, Better Jobs, Better Lives – Skills Strategy* (2012)
Riechert, SE and Post, BK (2010) From skeletons to bridges and other STEM enrichment exercises for high school biology. American Biology Teacher 72, 20-22.
SEEAG Report (2012) *Supporting Scotland's STEM Education and Culture*. Report of the Science and Engineering Education Advisory Group (SEEAG) January 2012.
http://www.scotland.gov.uk/Resource/0038/00388616.pdf

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