January 2011

Excellence in Science Education

Further Input from the Deans

Introduction and context

The Deans' Group welcomes the opportunity to amplify its previous input on what it believes should characterise excellence in the teaching of science in schools. This amplification is presented below for each of the three areas for which further comment was invited. This introductory section aims to set our advice in a broader context.

We recognise that the *Curriculum for Excellence* vision is viewed by many teachers as presenting a major challenge. A considerable culture change in the whole approach to education is implied, fundamentally to "liberate" the day-to-day experience of both learners and teachers from the tightly defined and closely focused programmes, busily specified in detail, that have increasingly dominated classroom practice over recent decades.

In the Deans' view, the most important learning outcome, across the STEM subjects, is to enable the learner to apply the skills and core knowledge acquired in new and different contexts. It is important for education to give the learner adequate opportunity to explore the applicability and power of key ideas and skills, and to become aware of their increasing proficiency in so doing.

The change in culture and practice involved in adjusting fully to the *Curriculum for Excellence* vision, across the whole school system in Scotland, is so considerable an undertaking that it might best be viewed as a journey rather than as a single step process. We would wish to encourage the greatest achievable change of practice in the current stage, but we accept that to carry the confidence of a majority of the teaching community some compromises may be required in a first stage. There are new qualifications well under way in development, and the structure and specification for these may be impracticable to revisit.

As a Deans' group, we are directly responsible for post-school education leading to professional level STEM specialists. We have to build on the capabilities of school leavers who have achieved what we judge to be the most relevant school qualifications in our areas. Our own curricula have evolved in response to the culture and capabilities of students emerging from the current regime. We believe that the *CfE* vision has the potential to generate considerable benefits, if implemented in a way that truly emphasises the ability to apply key skills and core understanding in new contexts. This could allow us to enhance our own provision much more easily and more effectively, in line with the similar principles dictated by the evolving nature and demands of our disciplines.

At our most recent meeting with the Cabinet Secretary for Education & Lifelong Learning, one outcome was encouragement to develop an ongoing forum for dialogue between the Deans' Group and relevant schools interests aiming to enhance mutual provision and arrangements for smooth transition from school to university study in STEM disciplines. The Excellence Group might think of commenting on how such a mechanism might be structured and supported as part of an ongoing strategy to achieve and to sustain world-leading excellence in STEM education in Scotland. We plan to discuss our own ideas on how to take this agenda forward at a meeting in mid-January. It would be helpful to arrange some continuing dialogue over the next couple of months, to help establish the most effective arrangements.

1. Inter-disciplinarity and cross-curriculum learning

In our previous position note the lead thrust was a strong plea to recognise the importance of the modern "STEM agenda" and the interconnectedness of the different disciplines. This is an important feature at all levels, notably including most of the research and industrial frontiers. Here we rehearse some of our hopes and concerns in a little more detail.

The different sciences do not exist within separate watertight boxes. The actual problems and applications addressed may characterise a specific discipline, but the ideas, skills and models developed to deal with them derive from the shared overall framework underpinning science. Some would argue that, for the various subject streams in school and early university science education, the main learning priority should be to develop general scientific capability, albeit that the contexts studied carry the flavour of a particular subject discipline.

We would advocate that, whenever a major new science topic or a fundamental law is introduced, its wider inter-disciplinary relevance should be explored, and also its dependence on ideas from other disciplines. Opportunities to do this are diverse and numerous (eg the implications of the laws of motion and mechanics can be explored in contexts relevant to biology). Such cross-referencing is relevant and important also between the sciences and engineering and technology. The applications of science underpinning the devices, infrastructure and medical services in the modern world are hugely significant, and the progress of science itself has been vitally dependent on the development of modern instrumentation and information processing. To aid this process we recommend that representatives from across the STEM disciplines meet to identify key points in the subject curricula where making interdisciplinary connections would be particularly relevant. An example, for instance, is to introduce pressure, energy and force when discussing water movement through cells. Subject-specialist teachers need to be given advice here.

There is both value in and scope for study of inter-disciplinary issues related to controversial science developments. Such study should form a part of every scientist's education. Another advantage of considering such topics is that connections will be made between disciplines so that an understanding of one discipline will help the learner to develop a greater understanding of another, and to be better able to communicate to other scientists across the disciplines.

A vital inter-disciplinary learning priority involves the interdependence of science and mathematics. We are adamant that science needs to be developed in a quantitative context, with a clear strategy for developing skills in developing and using relationships and equations and other relevant mathematical techniques. We expand on this aspect in section 3 below.

We have some concerns about how well the emerging curriculum can support the breadth of learning appropriate for future scientists and engineers. We note that, formally, the CfE structure 3 – 15 encourages inter-disciplinarity, but the way in which individual subjects are being developed in the Senior Phase makes cross-referencing difficult. In addition, inter-disciplinarity in guidance goes only up to level 3; curriculum narrowing will already be in effect (from S2?) for level 4. Further, whilst it has in the past been common for eight subjects to be studied through S3 and S4, the 160 hour standard for all subjects at all NQ levels suggests that the modal number of subjects taken in any year will be five, narrowing education overall, for most learners. In these circumstances it will be even more difficult than at present for learners to take all three main sciences and mathematics without overly narrowing their education as a whole. This position is exacerbated by the drafting of two distinct and complementary Biology Highers: learners who take only one of these will miss out on very important aspects of the discipline, whilst those who take both will inevitably further narrow their exposure to other important discipline areas. The Environmental Science Higher seems likely to cover yet other important areas of the biosciences that might consequently be left absent from the mainstream Biology course.

Whilst this section highlights the importance of the STEM-wide perspective in science education for all, we are acutely aware of the traditional strength of Scottish education as a whole, that traditionally has enabled a broad education to Higher level, allowing English, foreign languages and social subjects to taken alongside a good science and mathematics foundation.

Our previous note emphasised the importance of science for all, not just for those who may progress to studies and careers in STEM areas. We believe that it is unfortunate that there is no Higher level equivalent of the Nuffield *Science & Technology Issues in Society* courses recently developed in England. Such a course would give a better understanding of science for citizenship, suiting learners aiming for degrees in the humanities and social sciences, who might take just one H-grade in the sciences area.

The Deans would be very happy to contribute to more detailed and specific development discussions on how to address the challenges discussed in this section.

2. <u>Assessment</u>

The comments in our earlier position note summarise our overall view:

> *"It is widely held that the detailed structure and design of Higher Grade exams have heavily influenced the whole approach to teaching the sciences, and many claim that this applies from the beginning of secondary. Hence, getting the assessment "right" for the new generation of courses is of crucial importance. We should make it clear that from a university point of view, we would strongly support quite radical change. The whole spirit of Curriculum for Excellence is incompatible with the current model's reliance on recall of factual details and short taught "problem" procedures. The emphasis should be on demonstrating skills in applying an understanding of core concepts in new contexts. Questions should in general be more extended and more open. We appreciate that, for the sciences, a deal of trialling will be required to ensure that examinations and marking approaches are tuned to achieve the right standards, for each grade of award. Such change, however, is essential to raise the quality of science learning achieved."*

The significance of the assessment regime in influencing teaching would seem to be strongly evidenced in the reports of fairly widely shared unease among secondary teachers about implementing *CfE* for the S1 year before fully worked and confirmed details are available of the new S4 – S6 qualifications. Past teaching practice has often had a "nose to the grindstone" character, perceived necessary to ensure that all bases are covered in preparing for the wide range of characteristically predictable small items that will constitute the eventual examination papers. If educational practice is to change in favour of a more learner-active, skills-oriented and outward-looking model, it will be critical that this kind of approach is also seen to provide the best basis for succeeding in examinations. Such changes in the approach to learning will certainly provide a better preparation for the deeper challenges faced at subsequent stages of education and in employment, so the assessment model really needs to adapt accordingly.

Changing the approach to assessment presents difficult challenges. It requires being able to recognise and evaluate understanding, and thoughtful application of skills and core knowledge. We need to move away from a "gobbet" approach, which tests recall and single elements of information in modular pieces and does not test critical skills. We consider that it is important to set more-extended and more-open-ended questions with a reasonably wide degree of choice, questions which are often framed in new and unfamiliar contexts. Each question would carry several marks, and these should of course not be directly sub-allocated against a series of "gobbet" steps leading the candidate down a prescribed route.

There are two kinds of challenges in doing this. First, where questions are more extended and open-ended, relying on candidates to think rather than to remember, a more subtle approach to marking will be required. Answers will no longer simply be "right" or "wrong", but "better" (sometimes fully "right") or "poorer." The marks accorded have to reflect an appropriate distribution across the range of quality that will in the end justify different grades of award. Some decades have passed since such skills of judgement have been required of markers of school science exams.

The second challenge is a consequence of the first. Marking involving judgement, and especially where different tacks may be taken by different candidates, inevitably introduces an element of subjectivity. The precise final score awarded could differ, depending on the marker. In practice, through the use of second markers (now common practice in universities), such variability can be made very small, but it cannot be entirely eliminated. The existing assessment practice in science produces a precisely defensible final mark, but it does not reliably measure what is most important in learning the subject. The price for a better measure of educational achievement is to accept a more involved marking process and a less precisely determined final score. Universities are well-placed to advise on marking "open ended" assessments and can advise on well-worked marking schemes that enable learners to demonstrate an understanding beyond what may have been directly taught within the curriculum.

Given that candidates sit a fair number of exams in a diet, a "noise" level of 1 or 2 percent in individual scores is of no great overall consequence, except where this influences the grades awarded. The marking process needs to include a process of comparative review of borderline scripts. Where appeals are considered against grade decisions, these need to be judged by comparing the whole paper against others marked at the same level. Perhaps universities should be asked to rephrase entry requirements to focus more on a candidate's overall exam profile, and to be more flexible in relation to precise individual subject grades. For example it should be recognised that achieving 5 H-grade subject scores of 85, 85, 85, 85, 69 (AAAAB in grades) is significantly better than 72, 72, 72, 72, 72 (AAAAA). (This example assumes that percentage marks have been normalised such that 70 is the threshold score for grade A.)

In addition, the use of transcripts at subject level could provide much more useful information than a single overall examination grade or score. Transcripts could reflect the ability of students to achieve in different aspects of the assessment, to reflect their ability to achieve in different core skills: e.g. recollection of facts; interpreting data; demonstrating understanding of key concepts; ability to use examples from across disciplines; demonstrating critical evaluation. This approach has now been adopted in HE via the Higher Education Achievement Report, which provides graduates with a detailed transcript of their achievements and follows recommendations in the Burgess Report (see e.g. http://www.st-andrews.ac.uk/studenthandbook/attendance/transcripts and http://www.jisc.ac.uk/whatwedo/programmes/elearning/eadministration/hear.aspx).

The *CfE* approach to learning lends itself more readily to continuous assessment. Whilst this methodology is much used, successfully, in post-school education we are aware that its use within the school examination system is deeply distrusted, and has indeed built a reputation for producing unrealistically uniform high scores. There is deep hostility among many teachers to the idea of making greater use of it. Yet there has been encouraging development of such approaches for formative assessment, under the "assessment is for learning" drive. We would urge that efforts be made to encourage growth in the effectiveness and reliability of continuous assessment, and to give teachers more of a sense of "ownership" of standards (as is the case in FE and HE). One possible mechanism might be to use some extended, "formative" coursework as preparation for a related class exercise under controlled conditions.

Summative assessment does not add to learning; it simply measures it. The burden imposed should be minimised. Formative assessment, on the other hand, helps give the learner confidence in their developing skills and knowledge, and provides focus on areas needing strengthening. It could be useful to replace unit NAB assessments by a review of ongoing "assessment is for learning" formative work. In the longer term we would welcome abandonment of "unitisation" in general, particularly where this acts against integration of knowledge and skills and reduces the coherence of the course as a whole.

3. Mathematics

The importance of numeracy and mathematics was stressed at the outset of our position note, and was referenced again in section 1 above. Our earlier note commented: "Using these skills in the course of science study should significantly enhance the science itself, whilst also reinforcing progress in mathematics. A coherent collaborative strategy should be adopted across teaching departments. Among strands that are important are sensitivity to scale, applying proportion, handling probabilities, using graphs effectively, handling equations and algebra, and manipulating units. At more advanced levels the emerging significance of trigonometry, coordinate geometry, vectors and calculus should not be hidden."

First, we strongly encourage all learners interested in science to pursue mathematics to the same level as their science if they possibly can. For many STEM degree programmes Higher Mathematics is quoted as a prerequisite for entry. In some others it may not be listed as essential, but will always be helpful. For example, a study of the performance of students on a Computing Science course revealed that the Higher Maths grade held by entrants provided the strongest correlation indicator of subsequent performance on their course. Academics across the STEM disciplines have a strong consensus view that enhancing the mathematical skills of all entrants, including the majority who today hold good passes in H-grade Mathematics, would be of huge benefit to their future studies. If stronger mathematical skills can be achieved across Scottish schooling, this would provide a stronger platform to build on, and would in turn enhance the standards achievable in STEM degrees.

We welcome the fact that Mathematics, at least at H-grade, has been included as a mandatory component for the award of the Scottish Science Baccalaureate.

We strongly believe that a strategy to enhance the use of mathematics in science must run through the whole of schooling and that, in the 3 – 15 stage of *CfE* at least, careful analysis should be undertaken to optimise the opportunities for reinforcement of skills and understanding, by linking science and technology applications to basic studies undertaken in mathematics, and for mathematics teaching itself to highlight STEM-wide applications of techniques and concepts being introduced in a more abstract pure mathematical context.

It has to be recognised that interdisciplinary reinforcement during the Senior Phase of *CfE* is made somewhat more difficult given that not all learners will be studying both mathematics and the cross-referenced science. This clearly should not limit cross-referencing to topics covered at lower levels in the partner discipline. It should even be possible to refer to more advanced topics, albeit in a relatively more superficial way. We understand that an analysis in a forthcoming Royal Society study will show that, currently, the great majority of learners studying Higher Science in Scotland are indeed studying Mathematics at Higher in the same year. This may make it somewhat easier to make mathematics cross-references from within the various science courses.

Important areas include:

- to establish a clear overall development strategy dealing with symbols, units, algebra, scale, logs, . . .
  - to handle topics quantitatively at all levels
  - to build familiarity with scientific notation (eg 2 km = 2×10^3 m)
  - to recognise scaling, ratio and proportion
  - to ensure a precise understanding of quantities such as pH and the Avogadro constant
  - to reinforce algebra, eg $V = IR \Rightarrow I = V/R$
  - to develop abilities to work with units - understanding the difference between relative and absolute values and recognising quantities with compound units: eg concentrations, rates
  - to address the "algebra" of units in compound quantities and relationships
- to develop the idea of proof in general
- to ensure a carefully coordinated approach to using and interpreting graphs
- to recognise the significance of geometry across all of the sciences
- to build confidence in using angles, and in applying trig functions and vectors
- to establish an interdisciplinary strategy to develop skills in data handling & statistics: eg risk, variability
- to recognise that understanding logarithmic relationships is essential for all of the main science disciplines
- to note the intimate link between change and calculus: eg introducing calculus through graphical interpretation, such as deriving distance & acceleration from a v/t plot

We have advocated that all learners taking Higher courses in the sciences should if at all possible also take Higher Mathematics. We have also acknowledged that H-grade Mathematics is not flagged as a prerequisite for entry to, for example, many university courses in the biosciences (although this could change in future). A word of further explanation might be helpful. For entry level in Biology topics such as trig functions, vectors and calculus are not immediately important (though skills in data handling rather beyond those exhibited by current H-Maths holders would be useful). In later years of bio-degree studies the ideas and application of calculus, for instance, will become relevant, and while these can be picked up at that stage it is better for students to have a basic grounding before they reach this level. There is no doubt that a stronger set of mathematics skills would enhance the performance of all university science students.

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