CASE STUDY

Bridging the Gap: A Collaborative Approach to Mathematics Diagnostic Testing for STEM Student Transition in Scotland

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Abstract

This case study reports on a collaboration between Heriot-Watt University and University of Glasgow mathematics support services to develop a comprehensive diagnostic test based on Scottish Qualifications Authority[1] (SQA) Higher Mathematics, which is the essential foundation for most STEM degrees across Scottish Higher Education institutions.

Building upon the work of Shearman et al. (presented at CETL-MSOR 2023), our test was developed using NUMBAS's diagnostic mode, carefully mapped to SQA Higher Mathematics learning outcomes. This provides students with immediate feedback on their mathematical preparedness, whilst also generating detailed analytical data for mathematics support practitioners and academic staff. This paper details the development phases, including the initial pilot deployment and subsequent refinements based on user feedback and performance data. We further discuss our future plans to make the test openly available to students, lecturers, teachers and pupils across Scotland.

Keywords: Diagnostic testing, Transitions, Scotland.

1. Introduction

Diagnostic tests in mathematics are used widely in universities as a way of assessing student readiness for their chosen programme and informing both staff and individuals of potential gaps or weaknesses in pre-university knowledge. Some of these diagnostic tests have been administered to incoming students over many years and provide a comparison of incoming student competencies from cohort to cohort. Coventry University introduced their test in 1991 (Hodds 2021), while in the Scottish context, the University of Edinburgh (Akveld and Kinnear 2024) has administered a test in a digital format since 2011 (Maple TA from 2011-2017 and STACK (Sangwin 2025) since 2017). These are only two examples of long running diagnostic tests, but the use is widespread in the UK, Ireland and beyond (Hyland and O'Shea, 2022, Rylands and Shearman, 2022, Reddy et al. 2025, Cronin, Shearman and Reddy 2023). In Ireland, a study by Hyland and O'Shea (2022) showed that 70% of institutions used diagnostic testing, while Lawson (2003) showed that 60% of departments in the Learning Teaching Support Networks for Engineering, Maths Stats & OR, Physical Sciences and The UK Centre for Materials Education were delivering mathematics diagnostic tests. Gillard, Levi and Wilson (2010) conducted an email survey of maths departments across the UK where 60% of responding institutions reported that they delivered a diagnostic test for incoming students.

[1] The Scottish Qualifications Authority (SQA) changed its name to Qualifications Scotland after this paper was submitted for publication. All references to the SQA now relate to Qualifications Scotland.

Rylands & Shearman (2022) discuss the use and purpose of diagnostic testing in two case studies at Western Sydney University, while Cronin, Shearman & Reddy (2023) provide an overview and comparison of diagnostic testing in Ireland, Australia and the USA, highlighting the differences in implementation, as well as the shared purposes of student support and success.

In all the studies, the delivery of the diagnostic test varies from institute to institute and over time. Pen and paper tests were the preferred method in the responding institutions to the Gillard, Levi and Wilson (2010) survey while it seems that more recent testing is predominantly online. Though there is not a more recent survey to collate this, a few examples of online diagnostic tests are reported at ETH Zurich and the University of Edinburgh (Akveld and Kinnear, 2024), Western Sydney University (Shearman, Aziz and Pettigrew, 2024), and at Coventry University which switched to online in 2020 as a response to the Covid-19 pandemic (Hodds, 2021).

In Scotland, students pursuing a degree in STEM subjects are expected to have a good grasp of the mathematical concepts covered in Scottish Qualifications Authority (SQA) Higher Mathematics (Scottish Qualifications Authority, 2023). This is the standard mathematics qualification taken in either the penultimate or final year of school in Scotland and is an entry requirement for most[2] STEM degrees in Scotland. Without this background, students may struggle on their degree programme where new material will build upon this implied foundation.

However, it is widely recognised that not all students have the same educational background, with curriculums varying from country to country, and even from school to school. The increase of widening participation/access initiatives at institutions across the country (see O'Toole et al., 2024 for an overview of widening access) has led to, a very welcome, diversification of the student body, but this also increases the variability of pre-university knowledge. Due to the 4-year degree structure of a standard BSc degree in Scotland, the first year is often used as a time to 'level' the students' incoming knowledge. In this context, we realised that we had similar motivations for developing a diagnostic test and those can be summarised in two main aims:

1. Allow (any) teaching staff to identify the common weaknesses of their cohort of students.
2. Allow students to identify gaps in their knowledge/skills.

Crucially, in the context of both of these aims, there must be follow up interventions, advice and support to allow the growth and development of students' mathematical skills and confidence. While this is recognised (and briefly discussed) in this case study, the focus of the paper is on the development and deployment of the test.

Our test is deployed in NUMBAS (Lawson-Perfect et al. 2025), which is a freely available, open-source, online assessment system developed at Newcastle University that has an inbuilt adaptive algorithm, and we will discuss the methodology and process of developing the test in a step-by-step manner. In discussing the implementation, as well as the choices and development of questions, we aim to provide a practical guide for others who wish to develop a diagnostic test in this way. The test was first deployed to students in the 2024/25 academic year after which refinements were made, before being delivered to a larger number of students in academic year 2025/26.

[2] There are a few exceptions to this requirement, and it must be noted that there are some non-STEM subjects, such as economics, which also have this requirement.

2. Methodology

2.1 DIAGNOSYS Algorithm

As discussed above, our goal was to develop a tool that would help students identify their strengths and weaknesses within the SQA Higher Mathematics curriculum. However, it was also key for us that the test should not take too long for students to complete; this was partly to avoid intimidating students who are new to university with a long test, and also to improve completion rates by avoiding a situation where students give up halfway through. Ideally, the test should take less than 60 minutes so that it fits within a standard class.

Following the work of Shearman, Aziz and Pettigrew (2024), our approach was to create a test using the inbuilt *Diagnostic* mode within NUMBAS (Lawson-Perfect et al 2025). This uses an algorithm called DIAGNOSYS to create an adaptive test which is based on an underlying hierarchy of skills/topics, known as the *Knowledge Map*. The general idea is that students start somewhere in the middle of the hierarchy, and their next topic is determined by whether they get that question correct or incorrect:

- If they get the question correct, we assume that they would have also correctly answered any question on a prerequisite topic, and thus we mark those questions as correct without the student seeing them;
- If they get a question wrong, we assume that they would also have incorrectly answered any subsequent question building on that topic, and thus we mark those questions as wrong without the student seeing them.

For example, consider a toy version of the Knowledge Map shown in Figure 1. Suppose a student was initially presented with a question on Topic B. If they get that question correct, then the question for the prerequisite Topic A is also marked as correct and they would move on to trying the harder Topic C or D. If they get the initial question wrong (B), then the questions on Topics C and D would also be marked as incorrect and they would be given a chance to try the easier Topic A question.

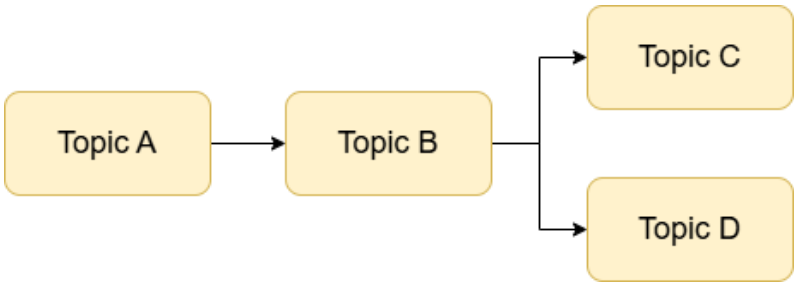


Figure 1. An example Knowledge Map showing four topics with the dependencies marked using arrows. It illustrates that Topic A is a prerequisite for Topic B, and Topic B is a prerequisite for Topics C and D.

Students continue to answer unmarked questions until there are none left and, in this way, the students are marked on a broad range of topics without having to see them all, helping to limit the amount of time required to take the test. We also hope that it avoids lower ability students becoming overwhelmed by seeing increasingly difficult questions. The first step of the test development is therefore to decide what skills need to be tested, and how to arrange them into the Knowledge Map.

2.2 Knowledge Map

Formally speaking, the Knowledge Map consists of a directed acyclic graph, where each vertex is a skill/topic that we wish to assess, and an arrow is added from vertex A to vertex B if Topic A is a prerequisite for Topic B. Crucial to the success of this approach is to create a Knowledge Map that accurately reflects the dependencies between different topics.

We began by determining the overarching *Learning Outcomes* that we wanted students to get feedback on. These are the categories that individual skills or topics[3] belong to, and at the end of the test, students are told whether or not they have mastered each Learning Outcome based on the percentage of questions within that category that get marked correctly. Our Learning Outcomes were decided by studying the SQA Higher Mathematics curriculum, along with looking at chapter titles in common textbooks for the course, so that test users would be able to easily find resources to act on their results, even if they do not have access to maths support. The Learning Outcomes chosen were:

- Numeracy - Fractions and Percentages (included in 2024, but removed for 2025)
- Algebra
- Polynomials
- Functions
- Powers and Logarithms
- Trigonometry - Angles and Graphs
- Trigonometry - Identities
- Straight Lines
- Vectors
- Differentiation (added in 2025)
- Integration (added in 2025)

Note that Differentiation and Integration were only left out of the first implementation due to time constraints, while Numeracy was removed to stop the test from becoming too long once these additional topics were added (and it is implicitly tested within the other Learning Outcomes).

Once we had the overall Learning Outcomes, we then used the details of the SQA Higher Mathematics curriculum (Scottish Qualifications Authority, 2023), along with our experience of what students often struggle with during their university studies, to determine the individual topics. Moreover, to help build the hierarchical structure, the skills listed in the curriculum were complemented with some prerequisite skills that are covered in the previous mathematics course, SQA National 5 Mathematics (roughly equivalent to GCSE Mathematics). For example, factorising a quadratic is already covered in the National 5 curriculum, but adding such skills to the test allows students with lower capabilities the opportunity to successfully answer questions at a lower level, hopefully avoiding demotivation. Once we had a full list of skills, each of these skills was created as

[3] A note of terminology: In NUMBAS, 'Learning Outcome' is the term used for the overarching area of mathematics while 'Topic' is used for a sub-area (i.e. the individual vertices of the Knowledge Map). In the SQA course specification document 'Skill' is used for both overarching areas of mathematics and their sub-areas.

a Topic in NUMBAS (see the NUMBAS Implementation section below for details) and each Topic was assigned to one of the Learning Outcomes listed above.

The next stage was then to add the dependencies, which we did by using our own experience. This was not always easy, and it sometimes depended on the particular question that would be chosen to assess the topic. For example, the prerequisites for an optimisation problem can depend on the type of function you are required to optimise, e.g. it would not be accurate to assume that because someone can optimise a polynomial expression that they can also differentiate trigonometric expressions. For this reason, there were several iterations of the Knowledge Map as we continued to come back and make edits once in the question selection stage.

A copy of the Knowledge Map created for our 2024 test is included in the appendix. This was edited for our 2025 version (see the Evolution section below), and we anticipate even further refinement once we start to analyse the 2025 results.

2.3 Question creation/selection

For each topic (i.e. vertex of the Knowledge Map), we needed to select at least one question that tests that particular skill. As discussed above, care was taken to ensure that the questions chosen reflected the choices made regarding dependencies when creating the Knowledge Map. NUMBAS supports the creation of different types of questions which allows for a more varied assessment, e.g. multiple-choice questions, mathematical expressions, number entry, matrices and interactive graphs/diagrams.

It is possible to provide more than one question per topic, but a given student will only see at most one of these - if they reach that topic, the algorithm will randomly select one of the questions. For example, using SOHCAHTOA to answer questions about right-angled triangles was kept as a single topic, but we added three questions so the students would randomly be assigned sin, cos or tan. It is useful to note that students do see the title of each question during the test, so we were careful to avoid giving away in the title which function they should choose.

Some of our questions were written specifically for this test, but many came from or were adapted from a bank of NUMBAS questions created by SCHOLAR (SCHOLAR 2025) – a digital learning initiative by Heriot-Watt University that provides resources for teachers and pupils in Scottish schools. Since we had approximately 90 topics to assess (and hence create questions for), this was a significant time-saver.

When choosing and writing questions, we aimed for them to have a randomised component so that students could repeat the test if they desired, without getting exactly the same questions. This even applied to graph-based questions where GeoGebra applets (GeoGebra, 2025) (which NUMBAS supports) were used to provide randomised graphs, e.g. plotting functions with randomised coefficients or parameters.

2.4 NUMBAS implementation

Once the Knowledge Map has been created and the questions have been written in NUMBAS, the implementation of the diagnostic test is straightforward. At the time of writing, the first step is to create a standard NUMBAS exam, and then from the Navigation pane, change the ‘Question navigation mode’ from ‘Sequential’ to ‘Diagnostic’.

At this point, we also chose to deselect the boxes that allow students to enable steps, reveal answers or regenerate questions since the purpose of the test is to establish their current strengths and

weaknesses. However, to avoid students' results being significantly impacted by a typographical, syntactical or basic calculation error, the algorithm automatically allocates them three retries to use during the test. If they get a question wrong, they can choose to use one of the retries to have another go at that same topic.

Once Diagnostic mode is selected, a Diagnostic pane will appear which has tabs for:

- Learning Objectives - these are the question categories that topics fall into, and are what students will get feedback on at the end of the quiz (e.g. 76% for Vectors);
- Topics - these are individual skills that you want to ask questions about (i.e. the vertices of your Knowledge Map);
- Diagnostic algorithm - here you can find (and customise) the DIAGNOSYS algorithm that will implement the marking described at the beginning of this section, so that students only see a selection of the questions.

Once you have added your Learning Objectives and Topics, you can then fill in the dependencies from your Knowledge Map using the Topics tab. For each topic, add other topics in the 'Depends on' box (those at the start of arrows ending at that vertex), and in the 'Leads to' box (those at the end of arrows starting at that vertex). An example is shown in Figure 2.

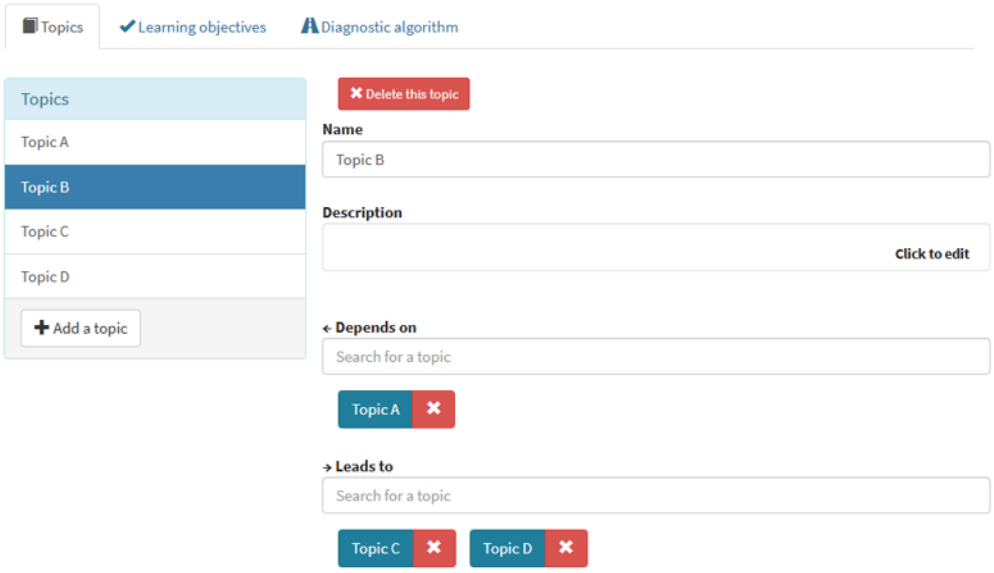
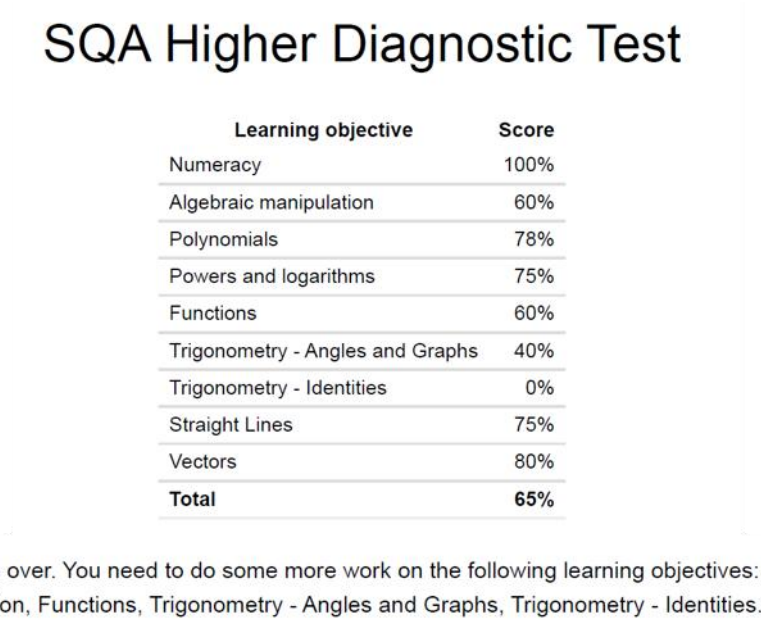


Figure 2. A screenshot from NUMBAS showing that, based on the Knowledge Map in Figure 1, Topic B would have Topic A in the 'Depends on' box, and Topics C and D in the 'Leads to' box. Similarly, Topic C would have Topic B in the 'Depends on' box, and nothing in the 'Leads to' box.

The final stage is then to go to the Questions pane (where the list of topics will appear) and add your chosen question(s) to each topic. This creates a working diagnostic test, although there are further things you can choose to customise in the Feedback and Navigation panes. For example, if a student skips a question, it is automatically marked as incorrect, and so, to avoid any confusion, we changed the 'action on leaving a question' to 'Prevent if unattempted' to ensure the student must enter something to proceed. We chose not to set a time limit as students may then receive feedback that they need to improve on a Learning Objective they did not have time to attempt. Additionally, we changed a setting in the DIAGNOSYS algorithm (on the Diagnostic pane) so that students start on

a random question, rather than the default of always on the middle question. Again, this makes repetition of the test more useful, as it is less likely they will follow the same path of questions if they start in different places.

At the end of the test, students receive instant feedback on their results, as shown in Figure 3.



SQA Higher Diagnostic Test

Learning objective	Score
Numeracy	100%
Algebraic manipulation	60%
Polynomials	78%
Powers and logarithms	75%
Functions	60%
Trigonometry - Angles and Graphs	40%
Trigonometry - Identities	0%
Straight Lines	75%
Vectors	80%
Total	**65%**

The test is over. You need to do some more work on the following learning objectives: Algebraic manipulation, Functions, Trigonometry - Angles and Graphs, Trigonometry - Identities.

Figure 3. A screenshot showing an example of the feedback students receive immediately on completing the test.

For delivery to our students, we chose to augment this feedback (by customising the algorithm within the Diagnostic pane) with extra information and links to the relevant maths support services at our institutions, as the follow-up to a diagnostic test is vitally important if it is to make an impact to student learning. Note that the threshold for the message “You need to do some more work on the following learning objective…” is customisable and can be set at a level of your choosing using the Feedback pane.

2.5 Delivery

2.5.1 Integration with Virtual Learning Environments

After the test has been developed within NUMBAS, there are a variety of ways in which it can be delivered to students, giving flexibility to the practitioner. The method chosen will depend on several factors – predominantly the Virtual Leaning Environment (VLE) used at the institution.

At the University of Glasgow, the test was made available to all students as an optional tool on the maths support Moodle (VLE) page. Delivery via Moodle was achieved by downloading the SCORM package from NUMBAS and uploading it as a Moodle activity which was easy to do.

At Heriot-Watt University, Canvas is the VLE used and at the time of the first deployment (September 2024), delivery of the test using the SCORM package did not work as expected and it did not integrate with the gradebook in the VLE. To address this challenge, the test was delivered in standalone mode, where the test runs in a web-browser and students downloaded their attempt data

at the end and sent it to us. This approach allowed some results to be gathered for test refinement but created issues: students did not always download and submit their attempt data, or they sent screenshots of instant feedback instead of the correct data files. It must be noted that the time of first deployment the 'Analyse attempt data' tool within NUMBAS (which decrypts and displays the attempt data) could not handle exams in diagnostic mode: the NUMBAS team helped to find a workaround and allow us to access the attempt data.

After following internal software approval processes, the NUMBAS LTI (LTI is Learning Tools Interoperability, which allows tools like NUMBAS to be used in different virtual learning environments and interact with areas of the VLE such as the Gradebook) was implemented by the Heriot-Watt Information Technology Team which addresses the issues found with the SCORM package and successfully integrated the test with the VLE. Within the VLE, the NUMBAS LTI provides summaries of the attempt data for the cohort, as well as individuals.

The summaries provided by the NUMBAS LTI (and equivalent csv file) do not give full attempt data such as the path taken through the test or the time spent on individual questions. Therefore, in order to interrogate the attempt data further (from both institutions) and find more detailed information, Python code was written to extract relevant information from the json file that can be download for each test attempt.

2.5.2 2024 Student Cohorts

Students with SQA Higher Mathematics as a prerequisite for their course at University of Glasgow were encouraged to take the test in order to get advice on which of the Maths Refresher sessions they would benefit from attending. While at Heriot-Watt University, in 2024, the test was made available to any student at the university, but it was made compulsory for first-year students taking their initial calculus course. This course was selected following a request from the lecturer, who sought a way to assess students' levels, identify weaknesses, and highlight gaps in prior knowledge. This HWU cohort led to around 100 test-takers, but only 21 complete result sets were obtained and used to inform refinements to the test alongside our own evaluation.

2.5.3 2025 Student Cohorts

By the start of the 2025/26 academic year, the technical obstacles had been resolved, enabling seamless delivery within the VLE without requiring students to submit attempt data manually. The test remained compulsory for first-year calculus students at Heriot-Watt University and was extended to foundation students on science programmes, resulting in 328 students of varying background levels of mathematics taking the test at HWU (note that all had SQA Higher maths as a prerequisite). As in 2024/25, the test was not delivered to any specific cohort at the University of Glasgow, but was available as an optional tool for students with SQA Higher maths as a prerequisite for their university course,

2.5.4 Communication

In both iterations of the test so far, a lot of care was taken over how the details of the test were communicated to the students in order to minimise any distress/anxiety associated with taking a test in the first few weeks of their university journey. A guide was produced to explain the reasons for diagnostic testing as well as practical information on using the NUMBAS platform and signposting students to the support available from maths support and their lecturers. To reinforce the message, maths support practitioners delivered in-person information sessions to the cohorts for whom the test was compulsory. At HWU, the first-year calculus class were permitted to take the test in their own time, while the foundation science students had to take the test in-class. This decision was at

the discretion of the course lecturer and, of course, leads to questions of academic integrity in the case where students took the test at home. However, the students only receive a very small percentage of their final grade from taking the test (or not), not the mark they received in the test. The aim was not to give them a grade, but to give the student and the lecturer information about the prior level of knowledge in order to support their learning.

The information sessions also explained that the diagnostic testing was being run alongside a research project, and while participants had to take the diagnostic test, they could opt in or out of the research survey. See the future work section for more information on this.

3. Results

From the 2024/25 deployment of the test, only a small amount of data was gathered; namely 21 complete attempt data files. From the 90 questions that are within the test, the average number of questions actually seen by the students was 51.14 due to the adaptive algorithm. Figure 4 shows a summary of the results (direct, raw scoring only) in the form of a heat map, where the colour corresponds to the score, each row relates to different respondents and each column to a different question. The low data return meant that the results did not give a complete picture of the cohort, but it was used to help us refine the test for the 2025 version.

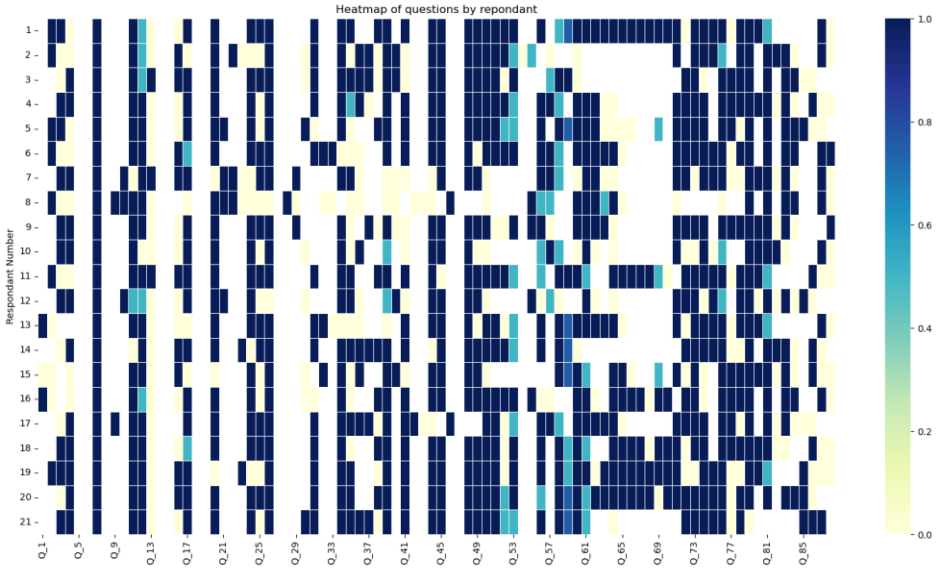


Figure 4. This heat map shows the raw score received by each respondant for each of the questions attempted.

At the time of the presentation at CETL-MSOR 2025, the second deployment was only just beginning but by the end of the first semester, 328 students had completed the test and a basic summary of results were produced (on a cohort level) for the lecturers involved. In this iteration, of the 89 questions within the test a student would see on average 43.57 questions during their attempt due to the adaptive algorithm. This reduction in the average number of questions seen by a student cannot be directly attributed to the change in the test from 2024/25 to 2025/26, as there is simply not enough data; it is merely a measure of the length of the test.

4. Discussion

4.1 Evolution

For the initial deployment, which needed to be ready for September 2024, we ran out of time and space to include the calculus topics. Even without these included, there were 90 topics in the test, and our trial runs were taking longer than our goal of 60 minutes. We therefore edited our Knowledge Map and questions before redeploying our test in 2025, which involved removing and/or merging some topics and adding in the calculus topics. Some of the principles we used to decide which topics to cut were as follows:

- We prioritised topics that were regularly used in university studies, based on our knowledge of the courses at our universities and the questions we are commonly asked by students, e.g. we removed the questions on calculating medians from the 'Straight Lines' Learning Objective, and the question from 'Trigonometry: Identities' asking students to express the wave equation as a single sin or cos expression;
- The Learning Outcome `Numeracy' was cut as the topics it contained were all prerequisites for Higher Mathematics, rather than part of the curriculum itself;
- Questions which were intended to be non-calculator (such as the question using exact angles in the `Trigonometry: Angles and Graphs' Learning Outcome) were removed as there is no way of guaranteeing students do not use a calculator;
- Time consuming questions were cut (this data was available from the json files), edited or merged to increase the efficiency of the test, e.g. the questions asking students to use the double angle formulae for sin and cos were merged into a single topic and the questions identifying various parameters from a trig graph (amplitude, phase, shifts) were adapted so they did not contain so many individual parts;
- We analysed the attempt data from the 2024 deployment and reviewed any questions which scored either very well or very poorly. We also looked at which questions no student had seen due to the algorithm marking them correctly or incorrectly based on other questions. This resulted, for example, in the three questions on varying levels of multiplying out brackets being merged into one, as two of them had not been seen by any of the students. We did, however, choose to keep some of the easier questions that had not been seen by any students, as most students would not see them (and hence they would not contribute to the length of the quiz), but they provided some achievable questions for struggling students.

After removing questions and adding in the two Learning Outcomes 'Differentiation' and 'Integration', our 2025 version of the test contained 89 questions. We anticipate that we will continue to make edits for the coming year.

4.2 Future Work

For the 2025 deployment of the test, we developed a short survey (full ethics approval has been granted for this research) to gather basic pre-university information from the students including:

- Did they take SQA Higher Mathematics?
- What was their last maths qualification?
- What grade did they receive?
- Likert scale questions assessing their confidence with the learning outcomes.

We are also planning to send out a follow up survey asking students how the test made them feel (both when being told they need to take it, and after they had taken it) and repeating the Likert scale

questions assessing their confidence with the learning outcomes. Using this data alongside the results of the test and students' first year grades, we hope to:

- Obtain a more complete picture of students' transitions to university, including common areas of weakness and/or lack of confidence;
- Further analyse the results of the test to assess whether it is a reliable indicator of success in first-year mathematics courses at university and refine the Knowledge Map and/or questions using techniques such as items analysis;
- Establish the effect of the test on students' confidence in mathematics;
- Investigate whether students experienced anxiety surrounding the test.

Our hope is to make a public version of the test that can be used widely in schools, colleges and universities across Scotland. One of the advantages of using NUMBAS for the test development is that there are multiple ways the test can be deployed to students so educators can integrate it to their systems and adapt feedback messages to their individual settings. The test has already been shared with the maths support service at the University of Aberdeen. By making this resource freely available to the wider academic community, we aim to support mathematics educators and student support services across the sector in addressing the persistent challenge of knowledge gaps that affect even high-achieving students during their transition to university-level mathematics

5. Appendix

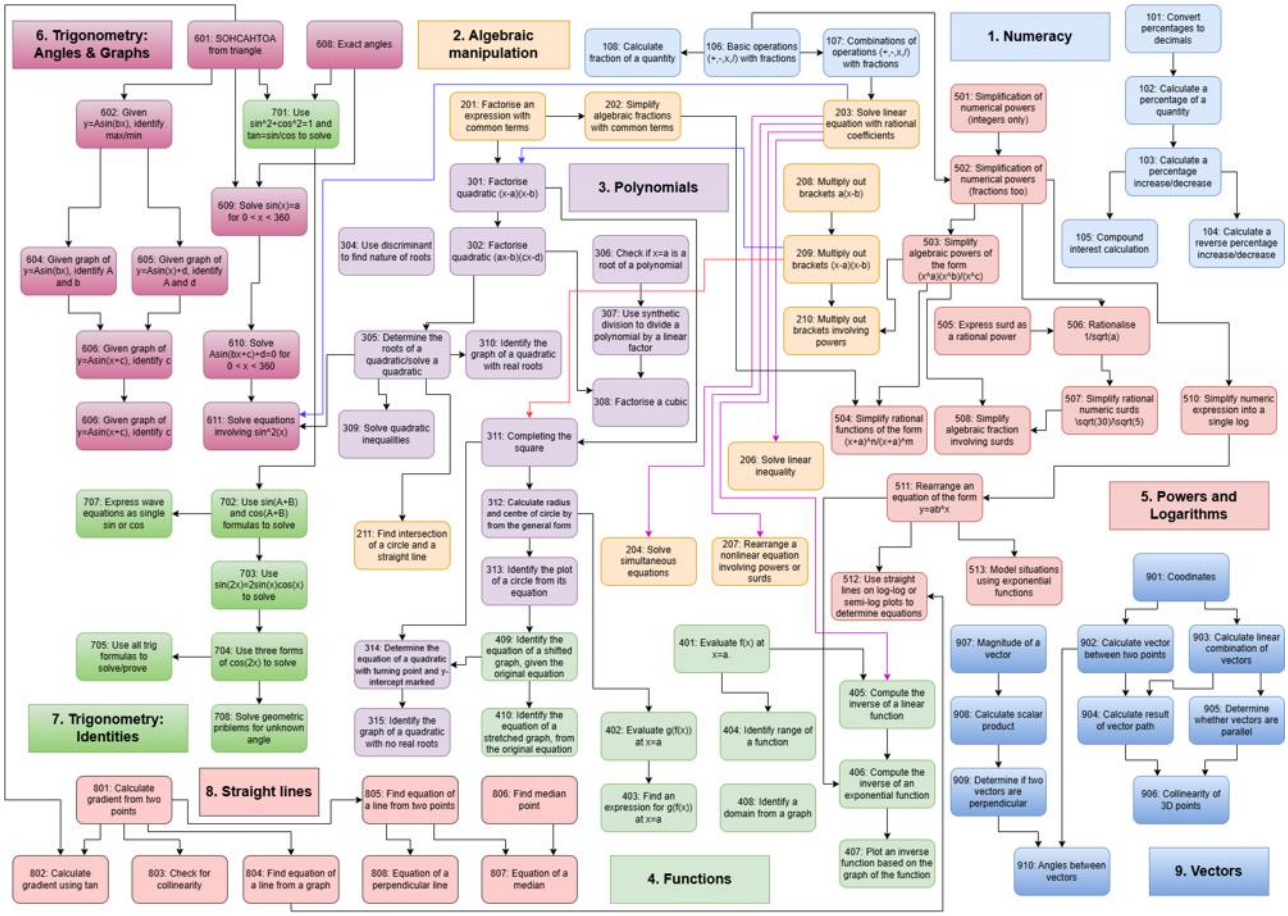


Figure 5. A copy of the Knowledge Map used for our 2024 version of the diagnostic test. Coloured arrows are designed to help the reader follow long arrows and have no other significance.

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