Teaching Python programming with automatic assessment and feedback provision

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Abstract—We describe a method of automatic feedback provision for students learning programming and computational methods in Python. We have implemented, used and refined this system since 2009 for growing student numbers, and summarise the design and experience of using it. The core idea is to use a unit testing framework: the teacher creates a set of unit tests, and the student code is tested by running these tests. With our implementation, students typically submit work for assessment, and receive feedback by email within a few minutes after submission. The choice of tests and the reporting back to the student is chosen to optimise the educational value for the students. The system very significantly reduces the staff time required to establish whether a student’s solution is correct, and shifts the emphasis of computing laboratory student contact time from assessing correctness to providing guidance. The self-paced nature of the automatic feedback provision supports a student-centred learning approach. Students can re-submit their work repeatedly and iteratively improve their solution, and enjoy using the system. We include an evaluation of the system and data from using it in a class of 425 students.

Index Terms—Automatic assessment tools, automatic feedback provision, programming education, Python, self-assessment technology

1 INTRODUCTION

1.1 Context

Programming skills are key for software engineering and computer science but increasingly relevant for computational science outside computer science as well, for example in engineering, natural and social science, mathematics and economics. The learning and teaching of programming is a critical part of a computer science degree and becoming more and more important in taught and research degrees of other disciplines.

This paper focuses on an automatic submission, testing and feedback provision system that has been designed, implemented, used and further developed at the University of Southampton since 2009 for undergraduate and postgraduate programming courses. While in this setting, the primary target group of students were engineers, the same system could be used to benefit the learning of computer science students.

1.2 Effective teaching of programming skills

One of the underpinning skills for computer science, software engineering and computational science is programming. A thorough treatment of the existing literature on teaching introductory programming was given by Pears et al. [1], while a previous review focused mainly on novice programming and topics related to novice teaching and learning [2]. Here, we motivate the use of an automatic assessment and feedback system in the context of teaching introductory programming skills.

Programming is a creative task: given the constraints of the programming language to be used, it is the choice of the programmer what data structure to use, what control flow to implement, what programming paradigm to use, how to name variables...
and functions, how to document the code, and how to structure the code that solves the problem into smaller units (which potentially could be re-used). Experienced programmers value this freedom and gain satisfaction from developing a 'beautiful' piece of code or finding an 'elegant' solution. For beginners (and teachers) the variety of 'correct' solutions can be a challenge.

Given a particular problem (or student exercise), for example to compute the solution of an ordinary differential equation, there are a number of criteria that can be used to assess the computer program that solves the problem:

1) correctness: does the code produce the correct answer? (For numerical problems, this requires some care: for the example of the differential equation, we would expect for a well-behaved differential equation that the numerical solution converges towards the exact solution as the step-width is reduced towards zero.)

2) execution time performance: how fast is the solution computed?

3) memory consumption: how much RAM is required to compute the solution?

4) robustness: how robust is the implementation with respect to missing/incorrect input values, etc?

5) elegance, readability, documentation: how long is the code? Is it easy for others to understand? Is it easy to extend? Is it well documented, or is the choice of algorithm, data structures and naming of objects sufficient to document what it does?

The first aspect – correctness – is probably most important: it is better to have a slow piece of code that produces the correct answer, than to have one that is very fast but produces a wrong answer. When teaching and providing feedback, in particular to beginners, one tends to focus on correctness of the solution. However, the other criteria 2 to 5 are also important.

We demonstrate in this paper that the assessment of criteria 1 to 4 can be automated in day-to-day teaching of large groups of student. While the higher-level aspects such as elegance, readability and documentation of item 5 do require manual inspection of the code from an experienced programmer, we find that the teaching of the high level aspects benefits significantly from automatic feedback as all the contact time with experienced staff can be dedicated to those points, and no time is required to check the criteria 1 to 4.

1.3 Automatic feedback provision and assessment

Over the past two decades interest has been rapidly growing in utilising new technologies to enhance the learning and feedback provision processes in higher education. In 1997, Price and Petre considered the importance of feedback from an instructor to students learning programming, especially looking into how electronic assignment handling can contribute to Internet-based teaching of programming [3]. Their study compares feedback given manually by several instructors to cohorts of conventional and Internet learning students, only a small fraction of which involved running the students' submissions. For the functional programming language Scheme, Saikkonen et al. described a system that assesses programming exercises with the possibility to analyse individual procedures and metrics such as run time [4]. A feedback system called “submit” for code in Java was introduced in 2003, which worked by allowing users to upload code, which would be compiled and (if the compilation was successful) run, with the output displayed for comparison with model output provided by the lecturer; the lecturer would manually grade the work later, and the system would also display this information [5]. Recognising the popularity of test-driven development and adopting that approach in programming courses, Stephen Edwards implemented a system, web-CAT, that would assess both the tests and the code written by students [6]. Shortly thereafter, another group produced a tool for automatically assessing the style of C++ programs [7], which students were encouraged to use, and which was also used by instructors when manually assessing assignments; it was found that the students started to follow many important style guidelines once the tool was made available.

By 2005 there was sufficient interest in the field of automatic assessment systems that multiple reviews were published [8], [9], highlighting the emergence of evidence that automatic assessment can lead to increased student performance [10], [11]. Another benefit realised with automatic assessment systems is greater ease in detecting plagiarism, tools for the purpose having been included in several of the systems surveyed. Also reported
on that year was CourseMarker [12], which can mark C++ and Java programs, and uses a Java client program to provide a graphical user interface to students.

A more recent review of automatic assessment systems [13] which highlighted newer development recommended that future systems devote more attention to security, and future literature describe more completely how the systems work. A work from MIT CSAIL and Microsoft introduces a model in which the system – provided with a reference implementation of a solution, and an error model consisting of potential correction to errors that students may make – automatically derives minimal corrections to students’ incorrect solutions [14]. Another relatively recent development is the adoption of distributed, web-based training and assessment systems [15], as well as the increasingly-popular “massive open online courses” or MOOCs [16]. A current innovation in the field is the nbgrader project [17], an open-source project that is designed for generating and grading assignments in IPython notebooks [18].

1.4 Outline
In this work, we describe motivation, design, implementation and effectiveness of an automatic feedback system for Python programming exercises used in undergraduate teaching for engineers. We aim to address the shortcomings of the current literature as outlined in the review [13] by detailing our implementation and security model, as well as providing sample testing scripts, inputs and outputs, and usage data from the deployed system. We combine the provision of the technical software engineering details of the testing and feedback system, with motivation and explanation of its use in a educational setting, and data on student reception based on 6 years of experience of employing the system in multiple courses and countries.

In Sec. 2 we provide some historic context of how programming was taught prior to the introduction of the automatic testing system described here. Sec. 3 introduces the new method of feedback provision, initially from the student’s perspective – who are the users from a software engineering point of view – then providing more detail on design and implementation. Based on our use of the system over multiple years, we have composed results, statistics and a discussion of the system in Sec. 4 before we close with a summary in Sec. 5.

2 TRADITIONAL DELIVERY OF PROGRAMMING EDUCATION
In this section, we describe the learning and teaching methods used in the Engineering degree programmes at the University of Southampton before the automatic feedback system was introduced.

2.1 Programming languages used
We taught languages such as C and MATLAB to students in Engineering as their first programming languages until 2004, when we introduced Python [19] into the curriculum. Over time, we have moved to teaching Python as a versatile language [20], [21] that is relatively easy to learn [22] and useful in a wide variety of applications [23], [24]. We teach C for advanced students in later years as a compiled and fast language.

2.2 Lectures
Lectures that introduce a programming language to beginners are typically scheduled over a duration of 12 weeks, with two 45 minute lectures per week. This is combined with a scheduled computing laboratory (90 minutes) every week (Sec. 2.3), and an additional and optional weekly “help session” (Sec. 2.4).

The lectures introduce new material, demonstrate what one can do with new commands, and how to use programming elements or numerical methods. In nearly all lectures, new commands and features are used and demonstrated by the lecturer in live-coding of small programs; often with involvement of the students. The lectures are thus a mixture of traditional lectures and a tutorial-like component where the new material is applied to solve a problem, and – while only the lecturer has a keyboard which drives a computer with display output connected to a data projector – all students contribute, or are at least engaged, in the process of writing a piece of code.

2.3 Computing laboratories
However, for the majority of students the actual learning takes place when they carry out programming exercises themselves.

To facilitate this, computer laboratory sessions (90 minutes every week) are arranged in which each student has one computer, and works at their own pace through a number of exercises. Teaching
staff are available during the session, and we have found that about 1 (teaching assistant) demonstrator per 10 students is required for this set up.

The lecturer and demonstrators (either academics or postgraduate students) fulfil three roles in these laboratory sessions:

(i) to provide help and advice when students have difficulties or queries while carrying out the self-paced exercises,
(ii) to establish whether a student’s work is correct (i.e. does the student’s computer program do what it is meant to do), and
(iii) to provide feedback to the student (in particular: what they should change for future programs they write).

Typically, prior to introducing the automatic testing system in 2009, the teaching assistants were spending 90% of their time on activity (ii), i.e. checking students’ code for correctness, and the remaining 10% of time can be used on (i) and (iii), while the educational value is overwhelmingly in (i) and (iii).

In practical terms, the assessment and feedback provision was done in pairs consisting of one demonstrator and one student looking through the student’s files on the student’s computer at some point during the subsequent computing laboratory session. The feedback and assessment was thus delivered one week after the students had completed the work.

2.4 Help session

In the weekly voluntary help session, computers and teaching staff are available for students if they need support exceeding the normal provision, would like to discuss their solutions in more depth, or seek inspiration and tasks to study topics well beyond the expected material.

3 NEW METHOD OF AUTOMATIC FEEDBACK PROVISION

3.1 Overview

In 2009, we introduced an automatic feedback provision system that checks each student’s code for correctness and provides feedback to the student within a couple of minutes of having completed the work. This takes a huge load off the demonstrators who consequently can spend most of their time helping students to do the exercises (item (i) in Sec. 2.3) and providing additional feedback on completed and assessed solutions (item (iii) in Sec. 2.3). Due to the introduction of the system the learning process can be supported considerably more effectively, and we could reduce the number of demonstrators from 1 per 10 students as we had pre-2009, to 1 demonstrator per 20 students, and still improve the learning experience and depth of material covered. There was no change to the scheduled learning activities, i.e. the weekly lectures (Sec. 2.2), computing laboratory sessions (Sec. 2.3), and help sessions (Sec. 2.4) remain.

In Sec. 3.2 “Student’s perspective” we show a typical example of a very simple exercise, along with correct and incorrect solutions, and the feedback that those solutions give rise to. Later sections detail the system design and work flow (Sec. 3.3) and in particular the implementation of the student code testing (Sec. 3.4), with reference to this example exercise.

3.2 Student’s perspective

Once a student completes a programming exercise in the computing laboratory session, they send an email to a dedicated email account that has been created for the teaching course, and attach the file containing the code they have written. The subject line is used by the student to identify the exercise; for example “Lab 4” would identify the 4th practical session. The system receives the student’s email, and the next thing that the student sees is an automatically generated email confirmation of the submission (or, should the submission not be valid, an error message is emailed instead, explaining why the submission was invalid. Invalid submission can occur for example if emails are sent from email accounts that are not authorised to submit code). At this stage, the student’s code is enqueued for testing, and after a short interval, the student receives another email containing their assessment results and feedback by email. Where problems are detected, this email also includes details of what the problems were. Typically, the student will receive feedback in their inbox within two to three minutes of sending their email.

We shall use the following example exercise, which is typical of one that we might use in an introductory Python laboratory, as the basis for our case study:
Please define the following functions in the file `training1.py` and make sure they behave as expected. You also should document them suitably.

1) A function `distance(a, b)` that returns the distance between numbers `a` and `b`.
2) A function `geometric_mean(a, b)` that returns the geometric mean of two numbers, i.e. the edge length that a square would have so that its area equals that of a rectangle with sides `a` and `b`.
3) A function `pyramid_volume(A, h)` that computes and returns the volume of a pyramid with base area `A` and height `h`.

We show a correct solution to question 3 of this example exercise in Listing 1. If a student who is enrolled on the appropriate course submits this, along with correct responses to the other questions, by email to the system, they will receive feedback as shown in Listing 2.

```python
def pyramid_volume(A, h):
    """Calculate and return the volume of a pyramid with base area A and height h."
    return (1./3.) * A * h
```

Listing 1: A correct solution to question 3 of the example exercise

```
Dear Neil O’Brien,

Testing of your submitted code has been completed:
Overview
=======
test_distance : passed -> 100% ; with weight 1
test_geometric_mean : passed -> 100% ; with weight 1
test_pyramid_volume : passed -> 100% ; with weight 1
Total mark for this assignment: 3 / 3 = 100%.
(Points computed as 1 + 1 + 1 = 3)

This message has been generated automatically. Should you feel that you observe a malfunction of the system, or if you wish to speak to a human, please contact the course team (course-help@uni.email.address).
```

Listing 2: email response to correct submission, additional line wrapping due to column width

If the student submits an incorrect solution, for example with a mistake in question 3 as shown in Listing 3 they will instead receive the feedback shown in Listing 4. Of course the students must learn to interpret this style of feedback in order to gain the maximum benefit, but this is in itself a useful skill, as we discuss more fully in Section 4.8.2 and comments from the testing code assist the students, as discussed in Section 3.4.5.

```python
def pyramid_volume(A, h):
    """Calculate and return the volume of a pyramid with base area A and height h."
    return (A * h) / 3
```

Listing 3: An incorrect solution to question 3 of the example exercise, using integer division

Within the testing feedback in Listing 4 the student code is visible in the name space `s`, i.e. the function `s.pyramid_volume` is the function defined in Listing 3. The function `correct_pyramid_volume` is visible to the test system but students cannot see the implementation in the feedback they receive – this allows us to define tests that compute complicated values for comparison with those computed by the student’s submission, without revealing the implementation of the reference computation to the students.

3.3 Design and Implementation

The design is based on three different processes that are started periodically (every minute) and communicate via file system based task queues with each other:

1) A `incoming queue` of incoming student submissions, initial validation and extraction of files and required tests to run (see high level flow chart in Fig. 1a)
2) A `queue of outgoing messages` that need to be delivered to the users and administrators which – in our email based user interface – decouples the actual testing queue from availability of the email servers (flow chart in Fig. 1b)
Dear Neil O’Brien,

Testing of your submitted code has been completed:

Overview
========

- test_distance : passed -> 100% ; with weight 1
- test_geometric_mean : passed -> 100% ; with weight 1
- test_pyramid_volume : failed -> 0% ; with weight 1

Total mark for this assignment: 2 / 3 = 67%.
(Points computed as 1 + 1 + 0 = 2)

Test failure report
====================

- test_pyramid_volume
  
  
  ```python
def test_pyramid_volume():
    # if height h is zero, expect volume zero
    assert s.pyramid_volume(1.0, 0.0) == 0.

    # tolerance for floating point answers
    eps = 1e-14

    # if we have base area A=1, height h=1, 
    # we expect a volume of 1/3.
    assert abs(s.pyramid_volume(1., 1.) - 1./3.) < eps

    # another example
    h = 2.
    A = 4.
    assert abs(s.pyramid_volume(A, h) - correct_pyramid_volume(A, h)) < eps

    # does this also work if arguments are integers?
    > assert abs(s.pyramid_volume(1, 1) - 1. / 3.) < eps
    E + where 0.3333333333333333 < 1e-14
    E + where 0.3333333333333333 = abs((0 - (1.0/3.0)))
    E + where <function pyramid_volume at
    0x7f0ce1af4e60>(1, 1)
    E + where <function pyramid_volume at
    0x7f0ce1af4e60> = s.pyramid_volume
  ```

Listing 4: email response to incorrect solution

As the subject line, the student has to use a pre-defined string (such as lab 1), which is specified in the assignment instructions, so the testing system can identify which submission this is. The identity of the student is known through the email address of the sender.

The testing system accesses the email inbox every minute, and downloads all incoming mails from it using standard tools such as fetchmail, or getmail combined with cron. These incoming mails are then processed sequentially as summarised in the flow chart in Fig. 1a.

1) The email is copied, for backup purposes, to an archive of all incoming mail for the given course and year.
2) The email is checked for validity in the following respects:
   a) the student must be known on this course (this is checked using a list of students enrolled on the course, provided by the student administration office); submissions from students who are not enrolled are logged for review by an administrator in case the student list was not correct or a student has transferred between courses;
   b) the subject line of the email must relate to a valid exercise for the course;
   c) all required files must be attached to the email, and these must be named as per the instructions for the exercise.
3) If the email is invalid (i.e., one or more of the above criteria are not met), an error report is created and enqueued in the outgoing email queue for delivery. The email explains why the submission is not valid, inviting the student to correct the problems and re-submit their work.
4) For a valid submission, the attachments of the incoming email containing the student’s code are saved and
5) an item is placed into the testing queue, including the exercise that is to be tested, the student’s user name, and names and paths of the files that were submitted.
6) For a valid submission, an email to the student is enqueued in the outgoing message queue that confirms receipt of the submission; the student can use this to evidence their submission and submission time, and it reassures the students that all required files
were present, and that the submission has entered the system.
7) For both valid and invalid submissions, the email is removed from the incoming queue.

### 3.3.2 Outgoing messages

The implementation of sending error messages and feedback reports to the students, and any other messages to administrators, is realised through a separate queue and process for outgoing messages (see Fig. 1b and discussion of this design in Sec. 3.4.7). This process is also used for weekly emails informing students about the overall progress (Sec. 3.4.6).

We note in passing that all automatically generated messages invite the student to contact the course leader, other teaching staff or the administrator of the feedback provision system should they not understand the email or feel that the system has malfunctioned; help can be sought by email or in person during the timetabled teaching activities.

### 3.4 Design and implementation of student code testing

The testing queue shown in Fig. 1c processes submissions that have been enqueued by the incoming mail processing script. The task is to execute a number of predefined tests against the student code in a secure environment, using unit testing tools to establish correctness of the student submission. As
we use Python for these courses in computation for science and engineering, we can plug into the testing capabilities that come with Python, and those that are provided by third party tools, such as nose [25] and pytest [26]. We have chosen the py.test tool because we have more experience with this system.

Here, we provide a brief overview of the testing process which is invoked every minute (unless an instance started earlier has not completed execution yet), with Sections 3.4.2 to 3.4.7 providing more details on the requirements and chosen design and implementation.

For each testing job found in the queue, the following steps are carried out (see the flow diagram in Fig. 1c):

1) The student files to be tested are copied to a sand-boxed location on the file system with limited access permissions (Sec. 3.4.1).
2) A dedicated local user with minimal privileges tries to import the code in a Python process to check for correct syntax.
3) If the import fails due to syntax errors an error message is prepared for the user and injected into the outgoing message queue. (See also Sec. 4.4.1 for a discussion.) The job is removed from the testing queue and the process moves to the next item in the queue.
4) If the import succeeds, the tests are run on the submitted code in the restricted environment (Sec. 3.4.2 to 3.4.4).
5) Output files (that the student code may produce) and testing logs are archived, marks extracted and all data are stored in a database which may be used by the lecturer to discover the marks for each student, for each question and assignment.
6) A feedback message for the student is prepared and injected into the outgoing message queue containing the test results (Sec. 3.4.5). This provides the student with a score for each question in the assignment, and where mistakes were found, provides details of the particular incorrect behaviour that was discovered. Listing 4 shows an example of such feedback.
7) The test job is removed from the queue.

We discuss additional weekly feedback to students in Sec. 3.4.6 and the system’s dependability in Sec. 3.4.7.

3.4.1 Security measures

By the nature of the testing system, it contains student data (names, email addresses, and submissions), and it is incumbent upon the developers and administrators to take all reasonable measures to safeguard these data against unauthorised disclosure or modification. We also require the system to maintain a high availability and reliability. The risks that we need to guard against can largely be divided into two categories: (i) genuine mistakes made by students in their code, and (ii) attempts by students – or others who have somehow gained access to a student’s email account – to intentionally access or change their own or other students’ work, assigned marks, or other parts of the testing system.

Experience shows that some of the most common genuine mistakes made by students include cases such as unterminated loops, which would execute indefinitely. Due to the serialisation of the tests in our system, this problem, if left unchecked, would stop the system processing any further submissions until an administrator corrected it. However, we have applied a POSIX resource limit [27], [28] on CPU time to ensure that student work consuming more than a reasonable and fixed limit is terminated by the system. We catch any such terminations, and in this case we have adopted a policy of informing the student by email, and giving them the opportunity to re-submit an amended version of their work. We apply similar resource limits on both disk space consumption and virtual memory size, in order that loops which would output large amounts of data to stdout, stderr, or a file on disk, or which interminably append to a list or array resulting in its consumption of unreasonable amounts of memory, are also prevented from causing an undue impact on the testing machine’s resources.

We address the potential that submitted code could attempt to maliciously access data about another student (or parts of the system) with a multi-faceted approach:

1) We execute the tests on the student code under a separate local user account on the server that performs the tests. This account has minimal permissions on the file system.
2) We create a separate directory for each submission that we test, and run the tests within this directory.
3) The result of the two previous points, assuming that all relevant file system permis-
sions are configured correctly, means that no student submission may read or modify any other student’s submissions or marks, nor can it read the code comprising the testing system.

4) The environment variables available to processes running as the test user are limited to a small set of pre-defined variables, so that no sensitive data will be disclosed through that mechanism.

5) We do not provide the students information about the file system layout, local account names, etc. on the host that runs the tests, to reduce the chance that students know of the locations of sensitive data on the file system.

3.4.2 Iterative testing of student code

We have split the exercises on our courses into questions, and arranged to test each question separately. Within a question, the testing process stops if any of the test criteria are not satisfied. This approach was picked to encourage an iterative process whereby students are guided to focus on one mistake at a time, correct it, and get further feedback, which improves the learning experience. This approach is similar to that taken by Tillmann et al. [29], where the iterative process of supplying code that works towards the behaviour of a model solution for a given exercise is so close to gaming that it “is viewed by users as a game, with a byproduct of learning”. Our process resembles test-driven development strategies and familiarises the students with test-driven development [30] in a practical way.

3.4.3 Defining the tests

There are an indefinite number of both correct and incorrect ways to answer an exercise, and to test correctness using a regression testing framework requires some skill and experience in constructing a suitably rigorous test case for the exercise. We build on our experience before and after the introduction of the testing system, ongoing feedback from interacting with the students and reviewing their submissions to design the best possible unit testing for the learning experience. This includes testing for correctness but also structuring tests in a didactically meaningful order. Comments added in the testing code will be visible to the students when a test fails, and can be used to provide guidance to the learners as to what is tested for, and what the cause of any failure may be (if desired).

Considering question 3) in the example exercise we introduced in Section 3.2, the tests that we carry out on the student’s function include the following:

1) Volume must be 0 when \( h \) is 0.
2) Volume must be 0 when \( A \) is 0.
3) If we have \( A = 1 \) and \( h = 3 \), volume must be 1.
4) If we have \( A = 3 \) and \( h = 1 \), volume must be 1.
5) If we have \( A = 1.0 \) (as a float) and \( h = 1.0 \) (as a float), volume must be \( \frac{1}{3} \).
6) If we test another combination of values of floating-point numbers \( A \) and \( h \) then the returned volume must be \( A \times h / 3.0 \).
7) If we have \( A = 1 \) (as an integer) and \( h = 1 \) (as an integer), volume must be \( \frac{1}{3} \).
8) The function must have a documentation string; this must contain several words, one of which is “return”.

In this very simple example, we set up the first group of criteria (1–6) to determine that the student has implemented the correct formula to solve the problem at hand. Criterion 7 tests for the common mistake of using integer division where floating-point division is required. The final criteria concern coding style. In this example, it is a strict requirement that the code is documented to at least some minimal standard, and the student will gain no marks for a question that is answered without a suitable documentation string.

Our implementation of the tests described above is given in Listing 5. In implementing these criteria, we avoid testing for exact equality of floating point numbers at any point in the testing process. Instead we define some tolerance (e.g. \( \text{eps} = 1e-14 \)), and require that the magnitude of the difference between the result of the student’s code and the required answer be below this tolerance. This avoids failing student submissions which have e.g. performed accumulation operations in a different order and concomitantly suffered differing floating-point round-off effects. As exercises become more complex and related to numerical methods, a different tolerance may have to be chosen.

We order the criteria so those that are most likely to pass are tested earlier, and we have chosen to stop the testing process at the first error encountered. This encourages students to address and correct one error at a time in an iterative process, if required, which is possible thanks to the short timescale between their submitting work
def test_pyramid_volume():
    # if height h is zero, expect volume zero
    assert s.pyramid_volume(1.0, 0.0) == 0.
    
    # if base A is zero, expect volume zero
    assert s.pyramid_volume(0.0, 1.0) == 0.
    
    # if base has area A=1, and the height is h=3,
    # we expect a volume of 1:
    assert s.pyramid_volume(1.0, 3.0) == 1.
    
    # if base has area A=3, and the height is h=1,
    # we expect a volume of 1:
    assert s.pyramid_volume(3.0, 1.0) == 1.
    
    # acceptable tolerance for floating point answers
    eps = 1e-14
    
    # if base has area A=1, and the height is h=1,
    # we expect a volume of 1/3.:
    assert abs(s.pyramid_volume(1., 1.) - 1./3.) < eps
    
    # another example
    h = 2.
    A = 4.
    assert abs(s.pyramid_volume(A, h) -
               correct_pyramid_volume(A, h)) < eps
    
    # does this also work if arguments are integers?
    eps = 1e-14
    assert abs(s.pyramid_volume(1, 1) - 1./3.) < eps
    
    # is the function documented well
    docstring_test(s.pyramid_volume)

Listing 5: testing code for example question

and receiving feedback (see Sec. 3.4.2). The implementation of the tests for py.test is based on assert statements, which are True when the student’s code passes the relevant test, and False otherwise. The final criteria, that the documentation string must exist and pass certain tests, is handled by asserting that a custom function that we provide to check the documentation string returns True. Of course, the tests must be developed carefully to suit the exercise they apply to, and to exercise any likely weaknesses in the students’ answers, such as the chance that integer division would be used in the implementation of the formula for the volume of a pyramid discussed above.

3.4.4 Clean code and PEP 8
In addition to the hard syntactic requirements of a programming language, there are often recommendations how to style and lay-out source code. We find that it is very efficient to introduce this to students from the very beginning of their programming learning journey.

For Python, the so-called “PEP 8 Style Guide” for Python Code is useful guidance, and electronic tools are available to check that code follows these voluntary recommendations for clean code. PEP 8 has recommendations for the number of spaces around operators, before and after commas, the number of empty lines between functions, class definitions, etc.

We use the pep8 utility to assess the conformance of the student’s entire submission file (which will usually consist of answers to several questions like the above) with the PEP 8 Style Guide. Our system counts the number of errors that are found, $N_{err}$, and penalises the student’s total score according to a policy (e.g. we may choose a policy of multiplying the raw mark that could be obtained for full PEP 8 conformance by $2^{-N_{err}}$, or of implementing any other desired mark adjustment as a function of that value).

3.4.5 Results and feedback provision to student
The results of the testing process are written to machine-readable files by py.test. For each tested submission, the report is parsed by our system, with one of a number of results being possible: the student code may have run completely in which case, we have a pass result or a fail result for each of the defined tests. Otherwise the student code may have terminated with an error which is most likely due to a resource limit being exceeded causing the operating system to abort the process, as discussed in Section 3.4.1.

The number of questions that were answered correctly (i.e. have no failed assertions in the associated tests) is counted and stored in a database. If there were incorrect answers, we extract a backtrace from the py.test output which we incorporate into the email that is sent into the student. The general format of the results email is to give a per-question mark, with a total mark for the submission, and then to detail any errors that were encountered. In the calculation of the mark for the assessment, questions can be given different weights to reflect greater importance or challenges of particular questions. For the example shown in Listing 2 all questions have the same weight of 1.

We described and illustrated a typical question, which might form part of an assignment, in Section 3.2. As shown in Listing 4 when an error is encountered, the results that are sent to the student include the portions of the testing code for the question in which the error was found that have passed successfully, and then indicate with
the > character the line whose assertion failed (in this case the 7th-last line shown). This is followed by a backtrace which illustrates that, in this case, the submitted `pyramid_volume` function returned 0 when it was expected to return an answer of \( \frac{1}{3} \pm 1 \times 10^{-14} \). The report also includes several comments, which are introduced in the testing code (shown in Listing 5), and assist students in working out what was being tested when the error was found. Here, the comment “does this also work if arguments are integers?” shows the student that we are about to test their work with integer parameters; that should prompt them to check for integer division operations. If they do not succeed in doing this, they will be able to show their feedback to a demonstrator or academic, who can use the feedback to locate the error in the student’s code swiftly, then help the student find the problem, and discuss ways to improve the code.

### 3.4.6 Statistical reporting to lecturers and routine performance feedback to student

The system records all pertinent data about each submission including the user who made the submission, as well as the date and time of the submission, and the mark awarded. We use this data to further engage students with the learning process, by sending out a weekly email summary of their performance to date, as shown in Listing 6. This includes a line for each exercise whose deadline has passed, which reminds the student of their mark and whether their submission was on time or not. For a student who has submitted no work, a different reminder is sent out, requesting they submit work, and giving contact details of the course leader, asking them to make contact if they are experiencing problems. Messages are sent via the outgoing queue (Sec. 3.3.2).

We also monitor missing submissions in the first couple of weeks very carefully and contact students individually who appear not to have submitted any work. Occasionally, they are registered on the wrong course, but similarly some students just need a little bit of extra help with their first ever programming exercises and by expecting the first submitted work at the end of the first or second teaching week, we can intervene early in the semester and help those students get started with the exercises and follow the remainder of the course.

After the deadline for each set of exercises, the course lecturers will generally flick through the code that students have submitted (or at least 10 to 20 randomly chosen submissions if the number of students is large). This helps the teacher in identifying typical patterns and mistakes in the students’ solutions, which can be discussed, analysed and improved effectively in the next lecture: once all student specific details are removed from the code (such as name, login and email address), submitted (and anonymised) code can be shown in the next lecture. We find that students clearly enjoy this kind of discussion and code review jointly carried out by students and lecturer in the lecture theatre, in particular where there is the possibility that their anonymised code is being shown (although only they would know).

The data for the performance of the whole class is made available to the lecturer through private web pages which allow quick navigation to each student and all their submissions, files and results. Key data is also made available as a spreadsheet, and a number of graphs showing the submission activity (some are shown in Figs. 3, 4 and 5 and discussed in section 4).

### 3.4.7 Dependability and resilience

The submission system is a critical piece of infrastructure for the delivery of those courses that have adopted it as their marking and feedback system; this means that its reliability and availability must be maximised. We have taken several measures to

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Dear Neil O’Brien,

Please find below your summary of submissions and preliminary marks for the weekly laboratory sessions for course ABC, as of Fri Jan 30 17:06:44 2015.

lab 2 : 25% Details: 1.00 / 4.00, submitted before deadline
lab 3 : 31% Details: 1.25 / 4.00, submitted before deadline
lab 4 : 0% Details: 4.00 / 4.00, but submission at 2014-11-14 20:39:02 was late by 13:39:02.
lab 5 : 80% Details: 4.00 / 5.00, submitted before deadline
lab 6 : 77% Details: 3.06 / 4.00, submitted before deadline
lab 7 : 75% Details: 3.00 / 4.00, submitted before deadline

The average mark over the listed labs is 48%.

With kind regards,

The teaching team (course-help@uni.email.address)

Listing 6: Typical routine feedback email
reduce the risk of downtime and service outages, and also to reduce the risk of data loss to a low level.

The machine on which the system is installed is a virtual machine which is hosted on centrally managed University infrastructure. This promises good physical security for the host machines, and high-availability features of the hypervisor, such as live migration [33], improve resilience against possible individual hardware failures. To combat the possibility of the data (especially the student submissions) being lost we have instituted a multi-tier backup system, which backs up the system’s data to multiple physical locations and to multiple destination storage media, so that the probability of losing data should be very small.

The remaining potential single point of failure is the University’s email system, which is required for any student to be able to submit work or receive feedback. In the case that the email system were to fail close to a deadline, we would have the choice of extending the deadline to allow submissions after the service was restored, and/or manual intervention to update marks where students could demonstrate that their submission was ready on time, depending on the lecturer’s chosen policy.

The internal architecture of the testing system was designed to be as resilient as possible, and to limit the potential impact of any faults. A key approach to this goal is the use of various (file system based) queues (Fig. 1) that decouple the different stages of submission handling and testing so that e.g. a failure of the system’s ability to deliver emails would not impede testing submissions already received. Emails are received into a local mailbox and are processed one item at a time so this is the first effective queue; receipt of emails can continue even if the testing process has halted. Valid submissions from processed emails are then entered into a queue for testing, the entries of which are processed sequentially. The receipt and testing processes generate emails, which are placed into an outgoing mail queue and are sent regularly, the queue items being removed only after successful transmission. This way, if the outgoing email service is unavailable, mails will accumulate in the queue and be sent \textit{en masse} when the service is restored.

Another key design decision was that each individual part of the receipt and testing process is carried out sequentially for each submission and is protected by lock files. Prior to processing received messages, the systems checks for existing locks; if these exist, the processing doesn’t start, and the event is logged (receipt of other emails continues as the receiving and processing are separate processes). If no locks are found, a lock is created, which is removed upon successful processing; any unexpected termination of the processing code will result in a lock file being left behind, so that we can investigate what went wrong and make any required corrections before restarting the system. The testing process itself is likewise protected by locking. A separate watch dog process alerts the administrator if lock files have stayed in place for more than a few minutes – typically each process completes within a minute.

In practice we have developed the system to the point that we have not had an unexpected failure require us to manually clean up and unlock in two years of production use, but should an unexpected bug be found, this design ensures that at most one submission will be affected (a copy will have been made before any processing was carried out, so even in this case there would be no loss of student data).

\section{Results}
\subsection{Testing system deployment}

The automatic testing system was first used at the University of Southampton’s Highfield Campus in the academic year 2009/2010 for teaching about 85 Aerospace engineers, and has been used every year since for growing student numbers, reaching 425 students in 2014/2015. The Southampton deployment now additionally serves another cohort of students who study at the University of Southampton Malaysia Campus (USMC) and there is a further deployment at the Indian Institute of Technology (IIT) Mandi and Madras campuses, where the system has been integrated with the Moodle learning management system, as described in Section 4.5.

The testing system has also been used in a number of smaller courses at Southampton, typically of approximately 20 students, such as one-week intensive Python programming courses offered to PhD students. It also serves Southampton’s courses in advanced computational methods where around 100 students have submitted assignments in C, as described in Section 4.6.
Fig. 2: Overview of the structure of the weekly computer laboratory session: A voluntary set of training exercises is offered to the students as a “training” assignment on which they receive feedback and a mark, followed by a compulsory set of exercises in the same topic area as the “laboratory” assignment which is marked and contributes to each student’s final mark for the course. Automatic feedback is provided for both assignments and repeat submissions are invited.

4.2 Case study: Introduction to Computing

In this section, we present and discuss experience and pertinent statistics from the production usage of the system in teaching our first-year computing course, in which programming is a key component. In 2014/15, there were about 425 students in their first semester of studying Acoustic Engineering, Aerospace Engineering, Mechanical Engineering, and Ship Science.

4.2.1 Course structure

The course is delivered through weekly lectures (Sec. 2.2) and weekly self-paced student exercise (Sec. 2.3) with a completion deadline a day before the next lecture takes place (to allow the lecturer to sight submissions and provide generic feedback in the lecture the next day). Students are offered a 90 minute slot (which is called “computing laboratory” in Southampton) in which they can carry out the exercises, and teaching staff are available to provide help. Students are allowed and able to start the exercise before that laboratory session, and use the submission and testing system anytime before, during and after that 90 minute slot.

Each weekly exercise is split into two assignments: a set of “training” exercises and a set of assessed “laboratory” exercises. This is summarised in Fig. 2.

The training assignment is checked for correctness and marked using the automatic system, but whilst we record the results and feed back to the students, they do not influence the students’ grades for the course. Training exercises are voluntary but the students are encouraged to complete them in order to practice the skills they are currently learning and prepare for the following assessed exercise which tests broadly similar skills.

Students can repeatedly re-submit their (modified) code for example until they have removed all errors from the code. Or they may wish to submit different implementations to get feedback on those.

The assessed laboratory assignment is the second part of each week’s exercises. For these, the students attempt to develop a solution as perfect as possible before submitting this by email to the testing system. This “laboratory” submission is assessed and marks and feedback are provided to the student. These marks are recorded as the student’s mark for that week’s exercises, and contribute to the final course mark. The student is allowed (and encouraged) to submit further solutions, which will be assessed and feedback provided, but it is the first submission that is recorded as the student’s mark for that laboratory.

The main assessment of the course is done through a programming exam at the end of the semester in which students write code on a computer in a 90 minute session, without Internet access but having an editor and Python interpreter to test the code they write. Each weekly assignment contributes of the order of one percent to the final mark, i.e. 10% overall for a 10 week course. Each laboratory session can be seen as a training opportunity for the exam as the format and expectations are similar.

4.2.2 Student behaviour: exploiting learning opportunities from multiple submissions

In Figure 3a, we illustrate the distribution of submission counts for “training 2”, which is the voluntary set of exercises from week 2 of the course.

The bar labelled 1 with height 92 shows that 92 students have submitted the training assignment exactly once, the bar labelled 2 shows that 76 students submitted their training assignment exactly
twice, and so on. The sum over all bars is 316 and shows the total number of students participating in this voluntary training assignment. 87 students submitted four or more times, and several students submitted 10 or more times. This illustrates that our concept of students being free to make stepwise improvements where needed and rapidly get further feedback has been successfully realised.

We can contrast this to Figure 3, which shows the same data for the compulsory laboratory assignment in week 2 ("lab2"). This submission attracts marks which contribute to the students’ overall grades for the course. In this case the students are advised that while they are free to submit multiple times for further feedback, only the mark recorded for their first submission will count towards their score for the course. For lab 2, 423 students submitted work, of whom 314 submitted once only. However, 64 students submitted a second revised version and a significant minority of 45 students submitted three or more times to avail themselves of the benefits of further feedback after revising their submissions, even though the subsequent submissions do not affect their mark.

Significant numbers of students choose to submit their work for both voluntary and compulsory assignments repeatedly, demonstrating that the system offers the students an extended learning opportunity that the conventional cycle of submitting work once, having it marked once by a human, and moving to the next exercise, does not provide.

The proportion of students submitting multiple times for the assessed laboratory assignment (Figure 3b) is smaller than for the training exercise (Figure 3a) and likely to highlight the difference between the students’ approaches to formative and summative assessment. It is also possible that students need more iterations to learn new concepts in the training assignment before applying the new knowledge in the laboratory assignment, contributing to the difference in resubmissions. The larger number of students submitting for the assessed assignment (423 ≈ 100%) over the number of students submitting for the training assignment (316 ≈ 74%) shows that the incentive of having a mark contribute to their overall grade is a powerful one.

4.2.3 Student behaviour: timing of submissions

In Figure 4 we show the submission timelines for all the voluntary “training” assignments that the students were offered every week. There are ten such scheduled assignments in total, and for each a line is shown. The assignments may be identified by their chronological sequence, as discussed in the following paragraphs.

In Figure 5, we show the same data but for the compulsory and assessed laboratory assignments (see Fig. 2 and Sec. 4.2.1 for a detailed explanation of the “training” and “laboratory” assignments).

Plot a) in Figure 4 and a) in Figure 5 show the “unique” student submissions counts for every exercise. With unique, we mean that only the first submission that any individual student makes for a given assignment is counted in the graph. On the contrary, subplots b) in Figure 4 and b) in Figure 5 show the “non-unique” submissions that include every submission made, even repeat submissions from any particular student for the same assignment.
Fig. 4: Submissions of voluntary training assignments as a function of time for (a) unique student participation for each assignment, (b) total number of submissions for each assignment. Labels L1…L10 and associated dashed vertical lines indicate time-tabled computing laboratory sessions 1 to 10 at Southampton; EA – end of autumn term; SS – start of spring term (Christmas break is between these dates); EX – exam. (See Sec. 4.2.3 for details.)
(a) Unique submissions of compulsory assessed laboratory assignments, showing the number of students participating as a function of time.

(b) Non-unique submissions of compulsory assessed laboratory assignments, showing the total number of submissions as a function of time.

Fig. 5: Submissions of compulsory and assessed laboratory assignments as a function of time for (a) unique student participation for each assignment, (b) total number of submissions for each assignment. Labels as in Fig. 4. Additional labels S2 to S10 (vertical dashed lines) indicate submission deadlines in Southampton; M2 to M10 (vertical dash-dotted lines in lower part of plot) show submission deadlines for students in Malaysia.
The unique plots allow us to gauge the total number of students submitting work to a given assignment (as a function of time), and the non-unique plots allow us to see the total number of submissions made by the entirety of the student body together.

We discuss the labels and annotations in Figure 4 first, but they apply similarly to Figure 5. The dashed vertical lines represent time-tabled computing laboratory sessions lasting 90 minutes where the students are invited to carry out the voluntary training and assessed laboratory assignment for that week in the presence of and with support from teaching staff. These time-tabled sessions, in which every student has a computer available to write their code, are labelled L1 to L10 in the figures.

The coloured symbols which are connected by straight lines count the number of submissions. In Figure 4a), the “training 1” assignment submissions are shown in blue, the next week’s “training 2” assignment submissions are shown in green, etc. There are ten scheduled laboratory sessions, and ten associated voluntary training assignments. There is one additional assignment at the end of the course which is offered to help revision for the exam, shown on the very right in Figure 4a) and b) in yellow without symbols.

Figure 5 shows submission counts for the compulsory assessed laboratory exercises. There were 9 such assessed assignments, starting in the second week of the course: while there is a voluntary training assignment in week 1, there is no assessed assignment laboratory assignment to give the students some time to familiarise themselves with the teaching material and submission system. From week 2 onward, there is one voluntary training assignment and one assessed assignment every week up to and including week 10. The students were given submission deadlines for the assessed laboratory assignments, and these deadlines for Southampton students are shown in the plots as dotted vertical lines labelled S2 to S10.

The course was delivered simultaneously at the University of Southampton (UoS) Highfield Campus in the United Kingdom – where about 400 students were taught – and the University of Southampton Malaysia Campus (USMC) in Malaysia – where a smaller group of about 25 students was taught. While following the same lecture material and assignments, these two campuses, due to different local arrangements and time zones, taught the course to different schedules, and the effect of this division is visible in all of the figures. The Malaysia students have different deadlines from the Southampton students, and these are shown as shorter vertical dash-dotted lines, labeled M2 to M10, towards the bottom of each plot in Figure 5. The deadlines of students in Malaysia (M) and Southampton (S) follow local holidays and other constraints, although they often fully coincide (S6 to S9), or are delayed by one week (S2 to S5).

We now discuss the actual data presented, starting with the voluntary training assignment submissions in Figure 4. Looking at Figure 4a) we see that the first training exercise had the largest number of submissions of any of the training exercises. About 300 of these submissions occurred during the first hands-on taught session L1, reflecting a large number of students who followed the recommended learning procedure of completing the voluntary exercises and doing so during the computing laboratory session in the presence of teaching staff, and who had sufficient resource and instruction available to do so.

The corresponding burst of submissions during the computing laboratory sessions L2 and L3 has decreased to about 175 and 150 submissions, respectively. The total number of students participating in these voluntary assignments in the first three weeks decreases from about 400 in week 1, to about 310 and about 270 in weeks 2 and 3, respectively. The total number of unique submissions reaches its minimum of about 80 in week 4 (the purple data set associated with hands-on session L4), and then starts to increase again for the remainder of the course.

In addition to the burst of submissions during the time-tabled sessions L1 to L10, we also note a significant number of submissions both before and after these sessions in Figure 4a) and b), reemphasising the flexibility that the system affords students as to where and when they submit their work. Anecdotal evidence, written feedback
from the students (Sec. 4.3) combined with the submission data suggests that some students will do the exercises as soon as they become available, and others prefer to do this during the weekend or evening hours. Many students see the offered computing laboratory sessions as an opportunity to seek support which they make use of if they feel this will benefit their learning.

Figure 4a shows that as the examination date (labelled as E at the right-hand side of the graphs) approached, a relatively small number of students started to submit solutions to the training exercises they had not submitted before as part of their revision and exam preparation. The same tendency is visible in Figure 4b with a slightly larger increase due to repeat submissions that cannot be seen in the graph in Fig. 4a.

We now discuss Figure 5 which shows the same type of data as Figure 4 but for the compulsory assessed laboratory assignments rather than voluntary training assignments. The most notable difference is that the total number of submissions remained high for all the assignments, reflecting that these assignments are not voluntary and do contribute to the final course mark. There is a slow decline of submissions present (from about 425 to 375 during the course, corresponding to approximately 10%) which is not unexpected and includes students leaving their degree programme studies altogether, suspending on health reasons, etc.

The vast majority of first submissions for the compulsory laboratory assignments, which contribute to the overall course marks, occur in advance of the deadline, as illustrated in Figure 5a where the deadlines are shown as vertical dotted lines.

The assessed assignment timings in Figure 5a show that submissions take place in different phases. The trend is visible in all the lines, but most clearly where the submission deadlines in Malaysia coincide with those in Southampton, i.e. laboratory sessions 6, 7, 8 and 9: the first submissions are received after the assignments have been published, and then a steady stream of submissions comes in, leading to an approximately straight diagonal line in Figure 5a. The second set of submissions is received during the associated laboratory session (shown as dotted line) where many students complete the work in the timetabled session. Following that, there is again a steady stream of submissions up to the actual deadline (shown as dotted line) where submissions accumulate. Very few (first) submissions are received after the deadline. The submissions in the second phase can be used to estimate student attendance in the laboratory sessions (see discussion in 4.8.4).

The University of Southampton Christmas break is also apparent, a period during which there are few new unique submissions (Fig. 5b), but slightly more new non-unique submissions (Fig. 5a) from students revising over the holiday and re-submitting assignments they had submitted before. It is reasonable to assume that they have re-written the code as an exam preparation exercise.

Trends seen in the voluntary submission data in Figure 4 such as a notable rise in the non-unique (i.e. repeat) submissions across all assignments in the days leading up to the exam, are also evident in Figure 5.

4.3 Feedback from students
While overall ratings of our courses using the automatic testing and feedback system are very good, it is hard to distinguish the effect of the testing system from that of, for example, an enthusiastic team of teachers, that would also achieve good ratings when using more conventional assessment and feedback methods.

We invited feedback explicitly on the automatic feedback system asking for voluntary provision of (i) reasons why students liked the system and (ii) reasons why students disliked the system. The replies are not homogeneous enough to compile statistical summaries, but we provide a representative selection of comments we have received below.

4.3.1 I like the testing system because...
The following items of feedback were given by the students when offered to complete the sentence "I like the testing system because..." as part of the course evaluation:

1) because we can get quick feedback
2) it is very quick
3) it provides a quick response
4) immediate effect
5) quick response
6) it gives very quick feedback on whether code has the desired effect
7) it provides speedy feedback, even if working at home in the evening
8) it worked and you could submit and re-submit at your own pace
9) I like the introduction to the idea of automated unit testing.
10) concise, straight to the point, no mess, no fuss. “Got an error? Here’s where it is. FIX IT!”
11) it was easy to read output to find bugs in programs
12) you can see where you went wrong
13) very informative, quick response
14) it reassures me quickly about what I do
15) it gave quick feedback and allowed for quick re-assessment once changes were made
16) feedback on quality of the code
17) it is fast and easy to use
18) it indicates where the errors are and we can submit our work as many times as we want
19) it is quick and automatic
20) it is automated and impartial
21) gives quick feedback, for training lets you test things quickly
22) it saves time and can give feedback very quickly. The re-submission of training exercises is very useful.

4.3.2 I dislike the testing system because…

The following items of feedback were given by the students when offered to complete the sentence “I dislike the testing system because…” as part of the course evaluation:
1) error messages not easy to understand
2) it takes some time to understand how to interpret it
3) sometimes difficult to understand what was wrong
4) it complains (gives failures) for picky reasons like wrong function names and missing docstrings. That’s not a complaint, it is only a machine.
5) it is a bit unforgiving
6) it is extremely [strict] about PEP 8
7) tiny errors in functions would result in complete failure of test.

Several comments (items 1 to 3) state that the feedback from the automatic testing system is hard to understand. This refers to test-failure reports such as shown in Listing 4. Indeed, the learning curve at the beginning of the course is quite high: the first 90 minute lecture introduces Python, Hello World and functions, and demonstrates feedback from the testing system to prepare students for their self-paced exercises and the automatic feedback they will receive. However, a systematic explanation of the assert statements, True and False values, and exceptions takes only place after the students have used the testing system repeatedly. The reading of error messages is of course a key skill (and the importance of this is often underestimated by these non-computer science students), and we like to think that the early introduction of error messages from the automatic testing is overall quite useful. In practice, most students use the hands-on computing laboratory sessions to learn and understand the error messages with the help of teaching staff before these are covered in greater detail in the lectures. See also Sec. 4.8.2.

A second set of comments relates to the harshness and unforgiving nature of the automatic tests (items 4 to 7). Item 7 refers to the assessment method of not awarding any points for one of multiple exercises that form an assignment if there is any mistake in the exercise, and is a criticism regarding the assessment as part of the learning process.

For items 4 to 6 it is not clear whether these statements relate to the feedback on the code or the assessment. If the comments relate to the code,
then they reflect a lack of understanding (and thus a shortcoming in our teaching) of the importance of documenting code and the importance of getting everything right in developing software (and not just approximately right).

### 4.3.3 Generic comments

The following comments on the feedback system were provided by students unprompted, i.e. as part of generic feedback on the course, and are in-line with the more detailed points made above:

1. **Fantastic real-time feedback with online submission of exercises.**
2. **Loved the online submission.**
3. **Really like the online submission system with very quick feedback.**
4. **Description in the feedback by automated system can be unclear.**
5. **Instant feedback on lab and training exercises was welcome.**
6. **Autotesting feature is VERY useful! Keep it and extend it!**
7. **The automatic feedback is fairly useful, once you have worked out how to understand it.**

In the context of enthusiastic endorsements of the testing system, we like to add our subjective observation from teaching the course that many students seem to regard the process of making their code pass the automatic tests as a challenge or game which they play against the testing system, and that they experience great enjoyment when they pass all the tests – be it in the first or a repeat submission (see also Section 3.4.2). As students like this game, they very much look forward to being able to start the next set of exercises which is a great motivation to actively follow and participate in all the teaching activities.

### 4.4 Issues

During the years of using the automatic testing system, we have experienced a number of issues which are unique to the automated method of assessment described here. We summarise them and our response to each challenge below.

#### 4.4.1 Submissions including syntax errors

When a student submits a file containing a syntax error, our testing code (here driven by the `py.test` framework) is unable to import the submission, and therefore testing cannot commence. Technically, such a submission is not a valid Python program (because it contains at least one syntax error). We ask the students to always test their work thoroughly before submitting, which should detect syntax errors first, and such submissions should not occur.

However, in practice, and given the large number of submissions (about 20 assignments per student, and currently 500 students per year), occasionally students will either forego the testing to save time, or will inadvertently introduce syntax errors such as additional spaces or indentation between checking their work and submitting it. From a purely technical point of view, the system is able to recognise this situation when it arises and we could state that any such submission is incorrect, and therefore assign a zero mark. However, these submissions may represent significant effort and contain a lot of valid code (for multiple exercises submitted in one file), so we have adopted a policy of allowing re-submission in such a scenario: if a syntax error is detected on import of the submission, the student is automatically informed about this, and re-submission is invited.

#### 4.4.2 Submissions in undeclared non-ASCII character encoding

We noticed an increasing trend, especially among international students, for submitting files in 8-bit character sets other than ASCII. Such files are accepted by the Python 2 interpreter so long as the encoding is declared in the first lines of the file according to the PEP263 [34]; but many of the students who were using non-ASCII characters were not describing their encodings at all. Our first response was to update our system to check for this situation, and upon discovering it, to send an automated email to the student concerned with a suggestion that they declare their encoding and re-submit. More recently, we have begun recommending the use of the Spyder [35] environment, whose default behaviour is to annotate the encoding of the file in question in a PEP 263–compliant manner. This has now virtually eliminated the occurrence of character encoding issues. For the few cases where these still arise, the automatic suggestion email, and (if required) personal support in scheduled laboratory and help sessions enables the students to understand and overcome the issue.

#### 4.4.3 PEP 8 style checker issues

As described in Section 3.4.3, we take advantage of the `pep8` utility [32] to assess the conformance of
the students’ submissions against the style recommendations of PEP 8.

Students find following style guidelines a lot harder than adapting to hard syntactic and semantic requirements of the programming language as they can solve the given exercises so that their code exhibits correct functional behaviour while not necessarily following the style guidelines. In our experience, it is critical to help students to adapt their own style habits to recommended guidelines, for example through tools that flag up non-confirming constructs immediately while editing code. One such freely available tool for Python is the Spyder [35] development environment, for which PEP 8-compatibility highlighting can be activated [36]. By encouraging all students to use this environment – at university machines and in installations of the software on their own machines for which we provide recommendations [37] – we find that they generally pick up the PEP 8 guidelines quickly.

As with so many things, if introduced early on, they soon embrace the approach and use it without additional effort in the future. Consequently, we penalise submissions that are not PEP 8 compliant from the second week onward.

One issue that arises with integrating PEP 8 guidelines into the assessment is that different software release versions of the pep8 tool may yield different numbers of warnings; this is partly due to changes in the view on what represents good coding style over time and partly due to bugs being fixed in the pep8 tool itself. This can result in unexpected warnings from the PEP 8-related tests. As a practical measure, we ensured that we are using the latest version of the pep8 checking tool, and have elected to omit those tests that are treated differently by other recent versions. The student body will generally report any such deviations between the PEP 8 behaviour on their own computer and the testing system, and help in identifying any potential problems here.

4.5 Integration with Moodle

Moodle (Modular Object-Oriented Dynamic Learning Environment) [38] is a widely-used open source learning management system which can be used to deliver course content and host online learning activities. It is designed to support both teaching and learning activities. The Indian Institute of Technology (IIT) Mandi and IIT Madras use Moodle to manage the courses at the institute level. When running a course, instructors can add resources and activities for their students to complete, e.g. a simple page with downloadable documents or submission of the assignments by prescribed time and date.

It was envisaged that integrating the automatic feedback provision system with Moodle would simplify the use of the automatic feedback system for IIT instructors and students, by allowing to submit and retrieve feedback through the Moodle interface that they use routinely already instead of using email, thus replacing the incoming queue process (Fig. 1a). Outgoing messages to administrators are still emailed using the outgoing email queue (Fig. 1b). The testing process queue (Fig. 1c) is used as in the Southampton deployment that is described in the main part of this paper.

In integrating the assessment system with the IIT Moodle deployment, we have used the Sharable Content Object Reference Model, SCORM, which is a set of technical standards for e-learning software products. The user front end is provided through the browser-based Moodle User Interface, while scripts at the back end make the connection to the automatic assessment system. The results are then fetched from the system and made visible to the student and the instructor. Using Moodle also helps the IIT to leverage the security that is already a part of the SCORM protocols.

The implementation at IIT is via a Moodle plugin designed such that, when a student submits an assignment, the plugin collects the global file ID of the submission and creates a copy of the file outside the Moodle stack. The plugin then invokes a Python script through exec(), transferring the location of file and file ID to the script. This Python script then acts as a user of the automatic feedback and assessment system, and directly enqueues the file for processing. The job ID inside automatic assessment system engine is returned to the Moodle plugin which maintains a database mapping job IDs to file IDs. After the file is processed by the automatic assessment system, the results are saved as files that are named after the (unique) job ID. When students access their results through Moodle, the relevant job IDs are retrieved from the database, allowing the corresponding results file to be opened, converted to HTML and published in a new page.
4.6 Testing of other languages

There should be no conceptual barriers for using the automatic testing and feedback system for testing of code written in other languages that provide unit testing frameworks. In particular JUnit [39] for Java could be used instead of py.test for Java programming courses. In this case, the execution of the actual tests (and the writing of the tests to run) would need to be done in Java, but the remaining framework implemented in Python could remain (mostly) unchanged, providing the student submissions handling and receipts, separation of testing jobs, a limited-privilege, limited-resource runtime environment, maintaining a database of results, and automatically emailing students their feedback.

As part of our education programme in computational science [40], we are interested in testing C code that students write in our advanced computational methods courses in which they are introduced to C programming. Students learn in particular how to combine C and Python code to benefit from Python’s effectiveness as a high level language but achieving high execution performance by implementing performance critical sections in C.

We are exploring a set of light weight options towards automating the testing of the C code within the given framework and our education setting:

1) Firstly, we compile the submitted C code using gcc, capturing and parsing its standard output and standard error to capture the number of errors and warnings generated.

2) We then run the generated executable under the same security restrictions as we use for Python, capturing its standard output and error, and potentially comparing them to known-correct examples.

3) We are also using the ctypes library to make functions compiled from students’ C code available within Python, so that they may be tested with tests defined the same way as for native Python code (see Listing 5).

The system that we built for testing Python code is modular enough that the above can be incorporated into the test work-flow for the courses where it is required. We note that it is now necessary to handle segmentation faults that may arise from calling the student’s C code: these may be treated similarly to the cases where resource limits are exceeded in testing Python code, causing the OS to terminate the process; the student’s marks may be updated if required, or a re-submission invited, in line with the course leader’s chosen educational policy.

4.7 Pre-marking exams

As well as assessing routine laboratory assignments, the system is also used to support exam marking. The format of the exam for our first year introductory programming course is a 90 minute session which the students spend at a computer, in a restricted environment. They are given access to the Spyder Python development environment to be able to write and run code but have no access to the Internet, and have to write code to answer exam questions which follow the format experienced in the weekly assignments. At the end of the exam, all the students’ code files are collected electronically for assessment. We pre-test the exam code files using the marking system with an appropriate suite of tests, and then distribute the automatically assigned marks and detailed test results and the source code to the examiners for manual marking. This enables the examiners to save significant amounts of time because it is immediately apparent when students achieve full marks and, where errors are found, the system’s output assists in swiftly locating them. It also increases objectivity compared to leaving all the assessment to be done by hand, possibly by a team of markers who would each have to interpret and apply a mark scheme to the exam code files.

The system has also been used to receive coursework submissions for a course leader who decided to exclusively manually assess the work. In this case, the system was configured simply to receive the submission, identify the user, store the submission, and log the date and time of submission of the coursework.

4.8 Discussion

In this section, we discuss key aspects of the design, use and effectiveness of the automatic testing system to support learning of programming.

4.8.1 Key benefits of automatic testing

A key benefit of using the automatic testing system is to reduce the amount of repeated algorithmic work that needs to be carried out by teaching staff. In particular establishing the correctness of student solutions, and providing basic feedback on their code solutions is now virtually free (once the testing code has been written) as it can be done automatically.
This allowed us to very significantly increase the number of exercises that students carry out as part of the course, which helped the students to more actively engage with the content and resulted in deeper learning and greater student satisfaction.

The marking system frees teaching staff time that would otherwise have been devoted to manual marking, and which can now be used to repeat material where necessary, explain concepts, discuss elegance, cleanliness, readability and effectiveness of code, and suggest alternative or advanced solution designs to those who are interested, without having to increase the number of contact hours.

Because of the more effective learning through active self-paced exercises, we have also been able to increase the breadth and depth of materials in some of our courses without increasing contact time or student time devoted to the course.

4.8.2 Quality of automatic feedback provision
The quality of the feedback provision involves two main aspects: (i) the timeliness, and (ii) the usefulness, of the feedback.

The system typically provides feedback to students within 2 to 3 minutes of their submission (inclusive of an email round-trip time on the order of a couple of minutes). This speed of feedback provision allows and encourages students to iteratively improve submissions where problems are detected, addressing one issue at a time, and learning from their mistakes each time.

This near-instant feedback is almost as good as one could hope for, and is a very dramatic improvement on the situation without the system in place (where the provision of feedback would be within a week of the deadline, when an academic or demonstrator is available in the next practical laboratory session).

The usefulness of the feedback is dependent upon the student’s ability to understand it, and this is a skill that takes time and practice to acquire. We elected to use the traceback output provided by py.test in the feedback emails that are sent to students in the case of a test failure, as per the example in Listing 4. The traceback, combined with our helpful comments in the test definitions, allows a student to understand under precisely which circumstances their code failed, and also to understand why we are testing with that particular set of parameters. Although interpreting the traces is not a skill that is immediately obvious, especially to students who have never programmed before, it is a skill that is usually quickly acquired, and one which all competent programmers should be well-versed in. We suggest that it is an advantage to encourage students to develop this ability at an early stage of their learning. Students at Southampton are well-supported in acquiring these skills, including timetabled weekly laboratories and help sessions staffed by academics and demonstrators. Once the students master reading the output, the usefulness of the feedback is very good: it pinpoints exactly where the error was found, and provides the rationale for the choice of test case as well.

A third aspect of the quality of feedback and assessment is objectivity. Because all of the submissions are tested to the same criteria, the system also improves the objectivity of our marking compared to having several people each interpreting the mark scheme and applying their interpretations to student work.

4.8.3 Flexible learning opportunities
A further enhancement to the student experience is that the system allows and promotes flexible working. Feedback is available to students from anywhere in the world (assuming they have Internet access), at any time of day or night, rather than being restricted to the locations and hours that laboratory sessions are scheduled. This means that the most confident students are free to work at their own pace and convenience. Those students who wish for more guidance and support can avail themselves of the full resources in the time tabled sessions. All the students can repeat training exercises multiple times, dealing with an error at once, when errors are discovered. They may also repeat and re-submit assessed laboratory exercises to gain additional feedback and deeper understanding, but in line with our policies, this does not change their recorded marks for assessed work.

4.8.4 Large classes
We have found that the assessment system is invaluable as our student numbers grow between years. Once exercises and didactic testing code are developed, the automatic testing and feedback provision does not require additional staff time to process, assess and feedback on student submissions when student numbers grow from year to year. Additional teaching staff in the practical sessions are required to maintain the student-staff ratio, but
the automatic system reduces the overall burden very significantly, and has helped us to deliver the training in the face of an increase from 85 to 425 students enrolled in our first-year introduction to computing course.

The flexible learning that the system allows (see Sect. 4.8.3) holds opportunities for more efficient space use. In the weekly hands-on computing laboratories, we currently provide all students their own computer for 90 minutes in the presence of teaching staff. With large student numbers, depending on the local facilities, this can become a time tabling and resource challenge.

We know from student attendance behaviour that the first two weeks see nearly all students attending the hands-on computing laboratories, but that student attendance in the computing laboratories declines significantly after week two, as – for example – the best students will often have completed and submitted the exercise before the time-tabled laboratory session, and some students will only come to the laboratory session to get help on a particular problem that they could not solve on their own; needing 15 minutes attendance rather than 90. As a result, it should be possible to ‘overbook’ computing laboratory spaces as is common in the airline industry, for example based on the assumption that only a fraction of the students will make regular use of the laboratory sessions in the later weeks. Figure 5a and its discussion shows supporting data of student laboratory attendance. We have not made use of this yet.

4.8.5 Student satisfaction

Student feedback on the automatic testing and learning with it has been overall very positive. We believe that the increased number of practical exercises is an effective way to educate students to become better programmers, and it is gratifying for teaching staff to see students enjoying the learning experience.

4.8.6 Software design

Our system design of having multiple loosely coupled processes that process student submissions with clearly defined sub-tasks, and pass jobs from one to another through file-system based queues has provided a robust system, which allowed us to connect it with other tools, such as for example the Moodle front-end for code submission in Madras and Mandi.

5 SUMMARY

We have reported on the automatic marking and feedback system that we developed and deployed for teaching programming to large classes of undergraduates. We provided statistics from one year of use of our live system, illustrating that the students took good advantage of the “iterative refinement” model that the system was conceived to support, and that they also benefited from increased flexibility and choice regarding when they work on, and submit, assignments. The system has also helped reduce staff time spent on administration and manual marking duties, so that the available time can be spent more effectively supporting those students who need this. Attempting to address some of the shortcomings of other literature in the field as perceived by a recent review article, we provided copious technical details of our implementation. With increasing class sizes forecast for the future, we foresee this system continuing to provide us value and economy whilst giving students the benefit of prompt, efficient and impartial feedback. We also envisage further refining the system’s capabilities at assessing submissions in languages other than Python.

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References

[1] A. Pears, S. Seidman, L. Malmi, L. Mannila, E. Adams, J. Bennedsen, M. Devlin, and J. Paterson, “A survey of literature on the teaching of introductory programming,” in Working Group Reports on ITiCSE on Innovation and Technology in Computer Science Education, ser. ITiCSE-WGR ’07. New York, NY, USA: ACM, 2007, pp. 204–223. [Online]. Available: http://doi.acm.org/10.1145/1345443.1345444.

[2] A. Robins, J. Rountree, and N. Rountree, “Learning and teaching programming: A review and discussion,” Computer Science Education, vol. 13, no. 2, pp. 137–172, 2003. [Online]. Available: http://www.tandfonline.com/doi/abs/10.1080/10409280308901600

[3] B. Price and M. Petre, “Teaching programming through paperless assignments: An empirical evaluation of instructor feedback,” SIGCSE Bull., vol. 29, no. 3, pp. 94–99, Jun. 1997. [Online]. Available: http://doi.acm.org/10.1145/268809.268849
[4] R. Saikkonen, L. Malmi, and A. Korhonen, “Fully automatic assessment of programming exercises,” in Proceedings of the 6th Annual Conference on Innovation and Technology in Computer Science Education, ser. ITICSE ’01. New York, NY, USA: ACM, 2001, pp. 133–136. [Online]. Available: http://doi.acm.org/10.1145/377435.377666

[5] A. Venables and L. Haywood, "Programming students need instant feedback!" in Proceedings of the Fifth Australasian Conference on Computing Education - Volume 20, ser. ACE '03. Darlinghurst, Australia, Australia: Australian Computer Society, Inc., 2003, pp. 267–272. [Online]. Available: http://dl.acm.org/citation.cfm?id=888405.888436

[6] S. H. Edwards, “Teaching software testing: Automatic grading meets test-first coding,” in Companion of the 18th Annual ACM SIGPLAN Conference on Object-oriented Programming, Systems, Languages, and Applications, ser. OOPSLA ’03. New York, NY, USA: ACM, 2003, pp. 318–319. [Online]. Available: http://doi.acm.org/10.1145/949344.949431

[7] K. Ala-Mutka, T. Uimonen, and H.-M. Jarvinen, “Supporting students in c++ programming courses with automatic program style assessment,” Journal of Information Technology Education: Research, vol. 3, no. 1, pp. 245–262, January 2004. [Online]. Available: http://www.editlib.org/p/1111892

[8] C. Douce, D. Livingstone, and J. Orwell, “Automatic test-based assessment of programming: A review,” J. Educ. Resour. Comput., vol. 5, no. 3, Sep. 2005. [Online]. Available: http://doi.acm.org/10.1145/1163409.1163409

[9] K. M. Ala-Mutka, “A survey of automated assessment approaches for programming assignments,” Computer Science Education, vol. 15, no. 2, pp. 83–102, 2005. [Online]. Available: http://dx.doi.org/10.1080/0899340050150747

[10] D. Woit and D. Mason, “Effectiveness of online assessment,” SIGCSE Bull., vol. 35, no. 1, pp. 137–141, Jan. 2003. [Online]. Available: http://doi.acm.org/10.1145/792458.792492

[11] J. English, “Experience with a computer-assisted formal programming examination,” SIGCSE Bull., vol. 34, no. 3, pp. 51–54, Jun. 2002. [Online]. Available: http://doi.acm.org/10.1145/67610.544432

[12] C. A. Higgins, G. Gray, P. Symeonidis, and A. Tsintsifas, “Automated assessment and experiences of teaching programming,” J. Educ. Resour. Comput., vol. 5, no. 3, Sep. 2005. [Online]. Available: http://doi.acm.org/10.1145/1163405.1163410

[13] P. Ihanola, T. Ahoniemi, V. Karavirta, and O. Seppälä, “Review of recent systems for automatic assessment of programming assignments,” in Proceedings of the 10th Koli Calling International Conference on Computing Education Research, ser. Koli Calling ’10. New York, NY, USA: ACM, 2010, pp. 86–93. [Online]. Available: http://doi.acm.org/10.1145/1930464.1930480

[14] R. Singh, S. Gulwani, and A. Solar-Lezama, “Automated feedback generation for introductory programming assignments,” in Proceedings of the 34th ACM SIGPLAN Conference on Programming Language Design and Implementation, ser. PLDI ’13. New York, NY, USA: ACM, 2013, pp. 15–26. [Online]. Available: http://doi.acm.org/10.1145/2491956.2462195

[15] E. Verd, L. M. Regueras, M. J. Verd, J. P. Leal, J. P. de Castro, and R. Queirs, “A distributed system for learning programming on-line,” Computers & Education, vol. 56, no. 1, pp. L1–L10, 2012. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S036013151100195X

[16] K. Masters, “A brief guide to understanding moocs,” The Internet Journal of Medical Education, vol. 1, no. 2, 2011.

[17] Jupyter Development Team, “nbgrader documentation,” Online, 2015, accessed at http://nbgrader.readthedocs.org/en/stable/ 4th August 2015.

[18] F. Pérez and B. Granger, “Python: A system for interactive scientific computing,” Computing in Science Engineering, vol. 9, no. 3, pp. 21–29, May 2007.

[19] H. Fangohr, “Teaching computational engineering using Python,” in EuroPython 2005, June 2005, Gothenburg, Sweden.

[20] D. Griffiths and P. Barry, Head First Programming: A learner’s guide to programming using the Python language. Sebastopol, CA: O’Reilly Media, 2009.

[21] A. Bogdanchikov, M. Zbarsky, and R. Suliyev, “Python to learn programming,” Journal of Physics: Conference Series, vol. 243, no. 1, p. 012027, 2013. [Online]. Available: http://stacks.iop.org/1742-6596/423/i=1/a=012027

[22] H. Fangohr, “A comparison of C, MATLAB, and Python as teaching languages in engineering,” in Computational Science – ICCS 2004, ser. Lecture Notes in Computer Science, M. Bubak, G. van Albada, P. Sloot, and J. Dongarra, Eds. Springer Berlin Heidelberg, 2004, vol. 3039, pp. 1210–1217. [Online]. Available: http://dx.doi.org/10.1007/978-3-540-25944-2_157

[23] P. S. Foundation, “Applications for Python,” Online, 2015, accessed at https://www.python.org/about/apps/ 31 March 2015.

[24] H. Fangohr, “Exploiting real-time 3D visualisation to enthuse students: A case study of using virtual python in engineering,” in Computational Science – ICCS 2006, ser. Lecture Notes in Computer Science, V. Alexandrov, G. van Albada, P. Sloot, and J. Dongarra, Eds. Springer Berlin Heidelberg, 2006, vol. 3992, pp. 139–146. [Online]. Available: http://dx.doi.org/10.1007/11758525_19

[25] J. Pellerin, “Nice is nicer testing for python,” Online, 2015, accessed at http://nice.readthedocs.org/en/latest/ 31 March 2015.

[26] H. Krekel, “pytest: helps you write better programs,” Online, 2015, accessed at http://pytest.org/latest/ 31 March 2015.

[27] The IEEE and The Open Group, “POSIX.1-2008 [The Open Group Base Specifications Issue 7],” 2013 Edition, available online. http://pubs.opengroup.org/onlinepubs/9699919799/9

[28] W. R. Stevens and S. A. Rago, Advanced programming in the UNIX environment, 3rd ed. Addison-Wesley, 2013.

[29] N. Tillmann, J. de Halleux, T. Xie, S. Gulwani, and J. Bishop, “Teaching and learning programming and software engineering via interactive gaming,” in Software Engineering (ICSE), 2013 35th International Conference on, May 2013, pp. 1117–1126.

[30] K. Beck, Test Driven Development: By Example, 1st ed. Addison-Wesley, 2003.

[31] The IEEE and The Open Group, “POSIX.1-2008 [The Open Group Base Specifications Issue 7],” 2013 Edition, available online. http://pubs.opengroup.org/onlinepubs/9699919799/7

[32] M.-A. Lemburg and M. von Lwiws, “PEP 263 - Defining python software,” Online, 2015, https://pypi.python.org/pypi/pep263

[33] A. M. Lemburg, A. Celebi, T. Garfinkel, and M. Cai, “The design and evolution of live storage migration in virtual machines,” in Proceedings of the 2011 USENIX Conference on USENIX Annual Technical Conference, ser. USENIXATC’11. Berkeley, CA, USA: USENIX Association, 2011, pp. 14–14. [Online]. Available: http://dl.acm.org/citation.cfm?id=2002181.2002195

[34] M.-A. Lemburg and M. von Lwiws, “PEP 263 - Defining python Source Code Encodings,” Online, 2001, accessed at https://www.python.org/dev/peps/pep-0263/ 15 Aug 2015.
[35] “Spyder – Scientific PYthon Development EnviRonment,” Online, 2015, accessed at https://github.com/spyder-ide/spyder, 7 August 2015.

[36] H. Fangohr, “Spyder tutorial,” Online, 2014, accessed at http://www.southampton.ac.uk/~fangohr/blog/spyder-the-python-ide-spyder-23.html.

[37] ——, “Anaconda installation summary,” Online, 2014, accessed at http://www.southampton.ac.uk/~fangohr/blog/installation-of-python-spyder-numpy-sympy-sciPY-pytest-matplotlib-via-anaconda.html, 30 July 2015.

[38] “Module object-oriented dynamic learning environment,” Online, 2015, accessed at http://moodle.org, 30 August 2015.

[39] “JUnit,” Online, 2002, accessed at http://junit.org, 4 August 2015.

[40] H. Fangohr, “Anaconda installation summary,” Online, 2015, accessed at http://www.southampton.ac.uk/~fangohr/blog/essential-tools-for-computational-science-and-engineering.html, 31 August 2015.