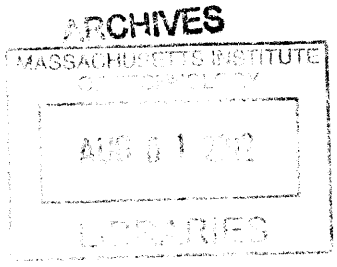
CAT-SOOP: A Tool for Automatic Collection and Assessment of Homework Exercises



by

Adam J. Hartz
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Submitted to the Department of Electrical Engineering and Computer Science
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Submitted to the Department of Electrical Engineering and Computer Science
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Abstract

CAT-SOOP is a tool which allows for automatic collection and assessment of various types of homework exercises. CAT-SOOP is capable of assessing a variety of exercises, including symbolic math and computer programs written in the Python programming language. This thesis describes the design and implementation of the CAT-SOOP system, as well as the methods by which it assesses these various types of exercises. In addition, the implementation of an add-on tool for providing novel forms of feedback about student-submitted computer programs is discussed.

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I would like to thank all of the people —students and staff alike —with whom I have worked as part of MIT's *6.01: Introduction to EECS I.* Were it not for the experience I gained through working with 6.01, I would not be the person I am today; at the very least, I'd be submitting a different thesis!

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Additional thanks go to Chris Buenrostro, Seleeke Flingai, Nora Mallory, Abiy Tasissa, and Adnan Zolj for their willingness to help, listen, and discuss, and for putting up with my rants about programming and education over the years.

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Chapter 1

Introduction

CAT-SOOP is a tool designed to automate the collection and assessment of homework exercises for a variety of disciplines. This thesis focuses on the design and implementation of CAT-SOOP, and on the methods by which it evaluates and provides feedback on submissions to different types of questions. Significant attention is also given to the Detective, an add-on to CAT-SOOP designed to provide novel types of feedback in response to student submissions to programming exercises.

Throughout, design decisions are considered in the context of other automatic tutors, principles of software engineering, and educational research.

1.1 Background

The history of systems like CAT-SOOP[1] dates back to 1926, when Pressey[20], noting the simplicity of many types of drilling exercises, presented a mechanical device capable of posing multiple choice questions to users, as well as collecting and scoring their submissions to said exercises.

Naturally, as technology has progressed since then, newer and more advanced systems have been developed to accomplish this same task, but more efficiently and for

[1] I will refer to these systems, which comprise components of Intelligent Tutoring Systems and Learning Management Systems, as "automatic tutors" throughout this document. Because this is something of an umbrella term, encompassing numerous projects with differing goals and features, I strive, when possible, to make clear the specific goals and features of the automatic tutor in question.

a broader range of problems. Checking of various types of problems is built into some Learning Management systems (e.g., Moodle[5] and LON-CAPA[11]), which often, in addition, take on the role of managing course materials, calendars, discussions, grades, etc.

Modern technologies have also allowed automatic tutoring systems to move beyond simple assessment of correctness, toward providing meaningful, conceptual feedback in response to students' submissions in a variety of contexts.

Bloom[2] has long since shown that one-on-one tutoring has dramatic benefits over traditional classroom instruction. Many automatic tutors thus attempt to recreate the feeling of interaction with a human tutor. It is certainly worth noting that such a system (i.e., an automatic tutor which accurately mimics a human tutor) has tremendous potential to help both students and staff alike, even if it works only for relatively simple concepts.

Since then, a wide variety of promising techniques have been attempted to improve the feedback generated by these systems. Among these are:

- Measuring clues about the user's affect (emotional state) and using that information to adjust the feedback presented[4]
- Using machine learning techniques to automatically generate hints for programming exercises[9]
- Recording a "trace" of submitted code as it is executed, and using this information to provide additional feedback[21]
- Attempting to create a conversational dialogue with the student[6]
- Creating an internal model of a student's understanding so as to individualize feedback[1]

While automatic tutors are not a replacement for in-person instruction, they can serve as an approximation thereof in a pinch, which can be invaluable to students. Particularly in introductory computer programming courses (but also in other fields,

as well), students often begin with little-to-no relevant experience. A direct consequence of this is that students spend a lot of time on assignments, getting stuck and attempting to debug their solutions, but often with poor technique; many require a lot of help in one-on-one or small group scenarios to get over these hurdles. Because of this, most introductory courses (at least in post-secondary education) hold "office hours," where professors or teaching assistants are available to help with homework exercises or conceptual review. In most cases, students find these hours quite helpful, but there are certainly limitations:

- Many problems that novices face are simple to diagnose and fix, but require a nontrivial amount of time to explain. While these problems are certainly still important to the students who face them, the teaching assistants' time may be better spent helping to solve more complex problems, particularly if the diagnosing and explanation of these errors can be automated.

- There are a limited number of hours in the day, and teaching assistants cannot spend all of their time holding office hours, or even making themselves available via e-mail. Frequently, students working late at night miss out on the benefit of office hours.

- Not all teaching assistants are equal, and no single teaching assistant has seen every problem that students will encounter. An automatic tutor that can provide feedback for a variety of common problems can help to create some sense of uniformity with respect to the feedback students receive on their work.

Because of these reasons and more, automatic tutors have the potential to have a really positive impact on students' learning experience, particularly for novices, whose common errors tend to be easier to diagnose and fix.

What's more, students enjoy working with automatic tutors, and find them beneficial[2]. Figure 1-1 shows the results from an end-of-term survey in MIT's *6.01 Introduction to EECS I*, which shows that students, in general, found the assignments

[2]Buy-in on the part of the students should not be understated as a contributing factor to the overall success of these systems, or of any pedagogical experiment.

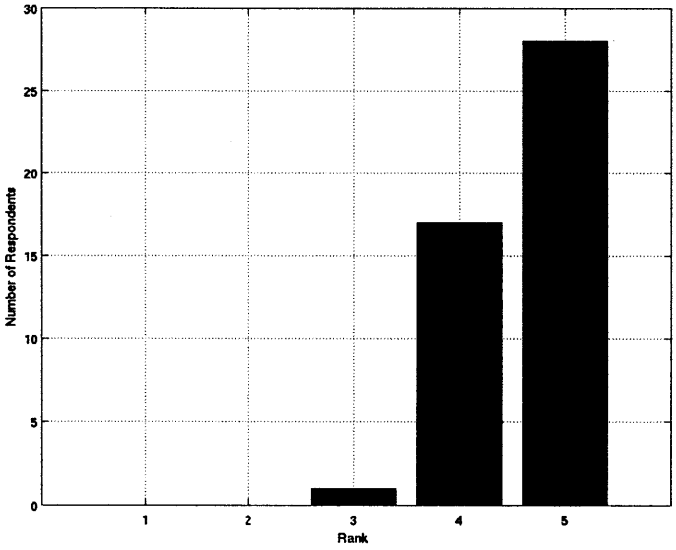


Figure 1-1: Students' responses to end-of term survey question relating to tutor2 for *6.01*, fall term 2011. Users were asked to rank their degree of agreement with the statement, "The on-line tutor helped me learn the 6.01 material," on a scale from 1 (total disagreement) to 5 (total agreement), with 3 as a neutral point. A total of 46 data points were collected.

delivered through the automatic tutor in *6.01* to be helpful. Similar results from an end-of-term survey in *6.003 Signals and Systems* (discussed in chapter 6) show that students also enjoy working with these types of software.

These results, along with the history, and the wide variety of available software in this area, have informed CAT-SOOP's design philosophy, as well as its implementation. Before discussing the specifics of its design, however, it is important to place CAT-SOOP in the context of the systems on which it is based, as well as to specify its purpose and design goals.

1.2 xTutor, tutor2, and CAT-SOOP

CAT-SOOP is the sibling of tutor2, an automatic tutor currently used in *6.01*. Both were developed in parallel[3], but completely ignorantly of one another; as time has gone on, however, certain parts of CAT-SOOP have found their way into tutor2, and vice versa[4].

In a sense, CAT-SOOP and tutor2 are both spiritual descendents of xTutor[5], an automatic tutor widely used at MIT throughout the 2000's, in a number of courses including *6.01*, *6.042 Discrete Math for Computer Science*, *6.034 Artificial Intelligence*, and the now-defunct *6.001 Structure and Interpretation of Computer Programs*. Both tutor2 and CAT-SOOP were designed as successors to xTutor in *6.01*; however, where tutor2 is essentially a port of xTutor to Python/Django, CAT-SOOP was started from a clean slate.

xTutor and tutor2 differ from CAT-SOOP in a number of respects. Firstly, CAT-SOOP is based on a design philosophy of simplicitly and minimalism. Thus, the focus of CAT-SOOP is extremely limited. CAT-SOOP's goal is to automate the collection and assessment of online homework exercises; intrinsically, this means that

[3]CAT-SOOP was originally designed for use in *6.01*; in fact, its name comes from the fact that CAT-SOOP was designed as an Automatic Tutor for Six-Oh-One Problems.

[4]In particular, CAT-SOOP's symbolic math checking, which is described in chapter 3, was ported into tutor2, and tutor2 and CAT-SOOP both currently use a scheme for checking Python code (decribed in chapter 4) which is an amalgamation of the schemes originally used by the two.

[5]`http://icampus.mit.edu/xTutor/`

tasks such as managing a course calendar, or managing final grading and weighting of various assignments, are not included in—and are not designed to be handled by—CAT-SOOP[6]. While tutor2 and xTutor don't go the way of full-fledged Learning Management Systems, both do include features beyond the assessment of student submissions.

xTutor (at least the version used in *6.01* most recently) and tutor2 also have a number of *6.01*-specific details built directly into their core systems. While this doesn't hinder the use of these tutors by other courses, it does mean that other courses have to ignore these parts of the systems if they intend to use tutor2 of xTutor. One major goal in CAT-SOOP's design was modularity, based on the belief that the core system should be as minimal as possible, and any course-specific content should make its way into the system via plug-ins or extensions. Teaching *6.01* using CAT-SOOP, for example, would still involve writing a good deal of course-specific material, but this material would live outside the core system. Because this course-specific material still needs to be written, another design goal was to make the creation of new content as easy as possible.

One additional point worth noting is that, while xTutor and tutor2 allow only one course per instance (and thus require the installation of a new instance for each course[7]), CAT-SOOP allows multiple courses to coexist in the same instance, in the hopes of providing a centralized location for students to submit online homeworks for multiple courses.

When considering the various components of CAT-SOOP in relation to other automatic tutors, this thesis will primarily make reference and comparisons to tutor2, and occasionally to xTutor (particularly in areas where xTutor and tutor2 differ significantly).

[6]Currently, CAT-SOOP does per-problem scoring, but does not have any notion of how scores from multiple problems should be combined to generate a final score. In an ideal system, the grading scheme is something that should be easy to change, and thus not something that is hard-coded into the core system.

[7]This has the additional downside that users need to create accounts on each instance separately.

1.3 Outline

The remainder of this thesis is structured as follows:

Chapter 2 discusses the design and implementation of the CAT-SOOP base system.

Chapters 3 and 4 discuss the means by which CAT-SOOP assesses submissions to symbolic math exercises and computer programming exercises, respectively.

Chapter 5 discusses the Detective, an add-on designed to provide a unique type of additional feedback on students' submissions to computer programming exercises. The design and implementation of the system, as well as the types of feedback it generates and the means by which it does so, are all discussed in this chapter.

Finally, chapter 6 provides concluding remarks, as well as suggestions for future research.

In addition, Appendix A contains complete source-code listings for select modules from CAT-SOOP and the Detective.

Chapter 2

Design

2.1 Typical Interactions with CAT-SOOP

CAT-SOOP is designed with two separate groups in mind: students and instructors. Thus, in designing the system, it was important to consider the ways in which each of these groups would potentially want to interact with the system. The list of instructors' desired features was gathered directly from instructors, but the list of students' desired features was speculative.

Students were expected to interact with the system primarily by logging in, navigating to a specific assignment, submitting answers, and viewing the resulting feedback, as well as viewing the solutions when they are made available. In addition, it was anticipated that students would want to be able to view a concise summary of their performance on a given problem or assignment[1].

Instructors were expected to want to be able to navigate, view, and complete assignments just as students (for testing purposes), but without the restrictions of completing the assignments within a certain range of dates. From an administrative standpoint, instructors also wanted to be able to view a student's scores, or his entire submission history for a problem; to update or modify scores; to make submissions

[1]While easy from a technical perspective, this presented an interesting issue, primarily because of CAT-SOOP's philosophy on grading. It is easy for a student to get an incorrect impression that the score being displayed to him is his actual score in the course; to minimize this possibility, scores are explicitly reported as "Raw Scores," and no assignment averages are displayed.

for a student; and to edit problems, assignments, and course announcements.

2.2 Choice of Languages and Libraries

When beginning any new project, consideration must also be given to the tools on which that project is built, and how they relate to that project's goals.

For CAT-SOOP, one of the main factors driving the choice of implementation was ease of access and ease of use for students. The easiest way to ensure easy access to CAT-SOOP for all students was to make it a web-based tool, so that any student with a computer and an Internet connection can access the system without having to install any additional software on his machine.

Beyond this, one hope was that executing and checking code written in the Python programming language would be straightforward, and that the system would be easily extensible. For these reasons, CAT-SOOP is written in the Python programming language[2] (it is compatible with versions 2.6 and 2.7).

For reasons of familiarity, CAT-SOOP is built on the cherrypy web framework[3], and interacts with a MySQL database using the SQLAlchemy Python module[4].

Because it is designed for use primarily in technical subjects, the ability to display mathematical formulae in the web browser is a crucial feature. Near its inception, CAT-SOOP used a homebrew SVG-based system for rendering mathematical formulae; currently, however, the MathJax JavaScript library[5] is used to render math, for reasons of browser compatability and aesthetics.

The Detective add-on, described in detail in chapter 5, was written in PHP, JavaScript (with jQuery), and Python, primarily because it was built as an extension to a piece of software built on these technologies.

[2] `http://python.org`
[3] `http://www.cherrypy.org/`
[4] `http://www.sqlalchemy.org/`
[5] `http://www.mathjax.org/`

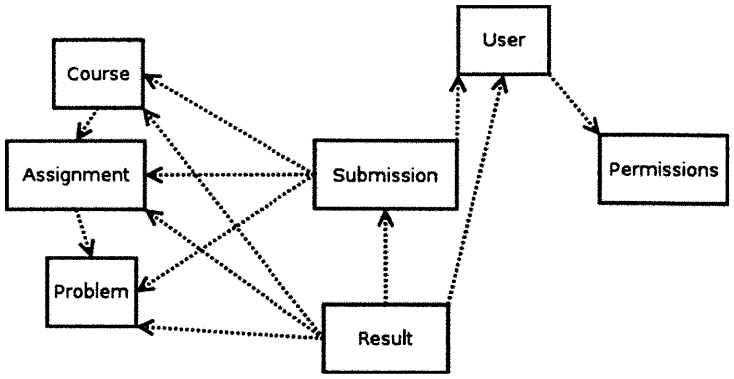


Figure 2-1: Graphical summary of the relationship between data structures in CAT-SOOP. Each line represents a "has-a" relationship.

2.3 Data Structures

This section describes the data structures used within CAT-SOOP. At times, the language in this section may shift back and forth between talking about objects in Python, and talking about entries in a MySQL database; it is worth noting here that each Python class described below (with the exception of the Question class) has an exact analog in CAT-SOOP's MySQL database, and so the concerns in each of these two realms will be lagely considered simultaneously.

2.3.1 Questions

Questions are central to the functionality of CAT-SOOP, as they represent requests for user input. Questions in the system each belong to a certain question type. These types are implemented as Python classes which inherit from a base Question class, and live in a specific location in the server's filesystem. Questions are never instantiated except as part of a Problem (see the following section regarding Problems), but CAT-SOOP keeps track of which Question Types are available in the system at all times.

Example question types which have been implemented for CAT-SOOP include: True/False, Multiple Choice, Short Answer, Numerical Answer, Symbolic Math (see chapter 3), Python Programming (see chapter 4), and PDF Upload.

Creating a new Question type amounts to making a new Python class which

inherits from the base Question class, and has the following attributes and methods:

- attributes `name`, `author`, `email`, `version`, and `date`, which contain the problem's metadata, represented as strings.
- a method `get_html_template`, which returns a template for displaying the problem to the user, and can display blank problems, as well as displaying a previous submission back to a student.
- a method `checker`, which takes as input a solution and a submission, and returns a tuple of four elements: the fraction of this problem's points the supplied submission earned, feedback to be given back to the user, a header for the feedback, and a submission that should be referenced as the previous solution the next time this problem is loaded[6])

2.3.2 Problems

In the CAT-SOOP terminology, "Problems" are collections of Questions, accompanied (potentially) by blocks of descriptive text, figures, formulae, or other resources.

Each student is allotted a certain number of submissions per problem, as specified in the problem's description. He may continue submitting new answers (and receiving feedback on them) until he runs out of submissions, but may stop at any time before reaching that point. A student's score on his most recent submission to a given problem will be taken as his score for that problem (see section 2.3.5 for details about how this information is stored).

2.3.2.1 Specification Language

Problems are specified using an XML markup language which is designed to be easy to use. For the most part, this language is plain HTML, but with a few additional tags added:

[6]This usually ends up being the submission currently being handled, but was necessary to prevent some undesireable behavior in PDF upload problems. In future versions, this will be cleaned up, and a nicer way to handle such situations will be found.

- The entire problem description must be surrounded by `<problem></problem>` tags.
- Inline mathematical formulae are specified through the use of `<math></math>` tags.
- "Display" mathematical formulae are specified through the use of `<dmath></dmath>` tags.
- Questions to be asked as part of a given problem are specified through the use of `<question></question>` tags.

Figure 2-2 shows an example of a problem description specified in this markup language. Note that options in the outer `problem` tag specify how many submits each student is allotted for a given problem, and that options in the `question` tag specify the number of points that a given question is worth, as well as a valid solution.

Problems can be edited within the browser[7] by individuals with proper permissions (see section 2.3.4).

2.3.3 Assignments and Courses

Problems are further grouped into Assignments. Each Assignment contains a number of problems, and has three dates associated with it, which control access to the problems contained therein:

- A release date, after which problems in the assignment can be viewed and submitted.
- A due date, after which time problems are marked as late.
- A solution date, after which time students can view solutions.

[7]Currently, the only way to edit problems is through the browser; however, multiple instructors have expressed interest in editing problems in their own favorite text editors. Thus, in future versions, Problems may be removed from the database and instead live in the filesystem as plain-text files, so as to allow for easy editing.

```
<problem title="Mystery Feedback" maxsubmits="5">

Consider the following feedback system where <math>F</math> is the
system functional for a system composed of just adders, gains, and
delay elements:

<br /> <br />

<center>
<img src="static/figures/mystery_system.png" />
</center>

<br /> <br />

If <math>\alpha=10</math> then the closed-loop
system functional is known to be:
<dmath>\left.{Y\over X}\right|_{\alpha =10}=~~{1+R\over 2+R}</dmath>

Determine the closed-loop system functional when <math>\alpha=20</math>.

<br /> <br />

<math>\left.{Y\over X}\right| _{\alpha =20} =</math> 

<question type="expression" points="4">
<solution>(2+2R)/(3+2R)</solution>
</question>

</problem>
```

Figure 2-2: Example problem specification, including graphics, math, and a single question.

Assignments are further grouped into courses. At its core, a course in CAT-SOOP is little more than a collection of Assignments, just as an Assignment is a collection of Problems. However, courses also have associated with them a set of ranks, which define the actions that certain individuals associated with that course are allowed to take, as well as a field containing announcements, which are displayed on a course's main page within CAT-SOOP.

2.3.4 Permissions

User permissions are controlled on a per-course basis. Each course has its own set of permissions levels ("ranks" in the CAT-SOOP terminology), and a user's rank in one course in no way affects his rank (and, thus, his permissions) in another course. For example, a student might be participating in one course as a TA, but in another as a student; it is crucial that he is allowed to take certain actions in one course, but not in another.

The CAT-SOOP system contains 8 different permissions bits, each of which can be enabled or disabled independently of the others:

1. "View" allows a user to view course materials as they are released.

2. "View Always" allows a user to view all course materials, regardless of release date. If a user's "view always" bit is set, his "view" bit is ignored.

3. "Submit" allows a user to submit solutions to problems, subject to release dates, due dates, and submission limits.

4. "Submit Always" allows a user to submit solutions to problems, regardless of time or submission limits. If a user's "submit always" bit is set, his "submit" bit is ignored.

5. "Grade" allows a user to edit other users' scores, and impersonation of other users (as described in section 2.4).

6. "Edit" allows a user to edit course materials, including release and due dates.

7. "Enroll" allows a user to add new users to a course, regardless of whether the course registration is open.

8. "Admin" allows a user to edit other users' permissions within the course, and open or close the course or registration.

Finally, each user has a single permissions bit (called the "in charge" bit) which, if set, allows him to modify global system settings.

2.3.5 Submissions and Results

CAT-SOOP's main goal is to facilitate the automatic collection and assessment of homework exercises. As such, it is important that the system keep a record of students' submissions to problems. In CAT-SOOP, this is handled by means of the Submission class.

Whenever a student makes a submission, a new instance of the Submission class is created, which contains the student's entire submission. Thus, every answer he ever submitted exists in the database in its entirety, along with the score he received on it. This information is useful for reviewing a student's peformance on a problem over time (for, e.g., assigning partial credit to a problem, or verifying a student complaint about faulty checking[8]).

Each student may have multiple Submissions for each problem he opens. With so many Submissions in the database, however, a need quickly arises for a sort of summary of a student's performance on a given problem, to avoid searching through numerous Submission objects to find the proper one, for scoring or for display of a problem; this is where the Result object comes in.

Each user has one Result object per problem. This object contains a reference to his most recent submission, as well as information about his current score. When he

[8]In systems where information about students' previous submissions is not stored, this can be a real pain. Firstly, there is no way to verify whether a student is telling the truth, and secondly, it can be very difficult to re-create (and subsequently fix) a checking error without knowing what exactly was submitted.

opens a problem, this Result object is loaded, and his previous responses and score (as gathered by loading his most recent submission, if any) are shown.

2.4 Grading and Impersonation

When an instructor views a student's submissions, he has the option of requesting only the student's most recent submission for that problem, or the student's entire history of submissions. He also has the ability to modify a student's score while viewing that student's submissions. When he does so, the student's original score remains in the database, but is augmented with information about the updated score, as well as the user who assigned him that score. Thus, when a problem is loaded for which a student has been specifically assigned a score by staff, that score will appear; for problems for which he has not been assigned a specific score by staff, CAT-SOOP's automatically-generated score will be displayed instead.

Staff may also want the ability to "impersonate" students. Impersonation is handled very differently in CAT-SOOP than in xTutor and tutor2. Both xTutor and tutor2 allow persistent impersonation in the sense that a user can impersonate a student for some duration of time, during which the system will behave as though he is the student he is impersonating. In xTutor, when one impersonates a student, a complete copy of that student's data is created and used as the impersonator's data until he is done impersonating the student. This gives the impersonator the freedom to do as he pleases while masquerading as the student, with no possibility of impacting the student's actual state in the system. In tutor2, when one impersonates a student, the system simply treats all actions he takes as though they had been taken by the student he is impersonating. This means that the impersonator can modify a student's state in the system if he so desires (or by accident, if he is not careful). Both of these schemes have positives and negatives associated with them, and neither is a clear-cut "better" solution.

CAT-SOOP does not allow persistent impersonation. Instead, a staff member may make submissions as a user if he needs to (or wants to). The staff member

does not "become" the student in the system's eyes, but any submission he makes in this fashion will be treated as though it were made by the student (although the submission is stored with additional information about who actually made it[9]).

[9]Another design goal of CAT-SOOP worth mentioning is that all important actions should be logged. Every submission, entry of grades, modification of problems, etc, should result in something being logged to the database. Having this information makes retrospection (in the event of a complaint, or a system failure) possible. xTutor keeps an even more detailed log, including every page load. tutor2 does the same, but misses some important information when logging students' submissions to problems.

Chapter 3

Evaluating Symbolic Math

CAT-SOOP underwent a pilot test in MIT's *6.003 Signals and Systems* in fall term 2011, where it was used almost exclusively to assess students' responses to mathematical questions. One easy way to approach this problem would have been to force the instructors to phrase all of the questions they wanted to ask in forms already allowed in the base system (e.g., instead of asking for a symbolic expression, ask for a numerical answer corresponding to that expression evaluated with certain values for each variable).

However, this seemed particularly restrictive, and so CAT-SOOP's symbolic math checking routines came to be. Currently, the system is capable of checking two main types of symbolic math: symbolic expressions, and numerical ranges, which are discussed in detail in the following sections. An example of CAT-SOOP's display during the solving of these types of problems can be seen in figure 3-1.

3.1 Mathematical Expressions

Appendix A (section A.1.1) contains the full source-code listing for `expressions_ast.py`[1], which is responsible for handling symbolic expressions in CAT-SOOP.

[1]This style of checking is used in both CAT-SOOP and tutor2, so it exists as a stand-alone module.

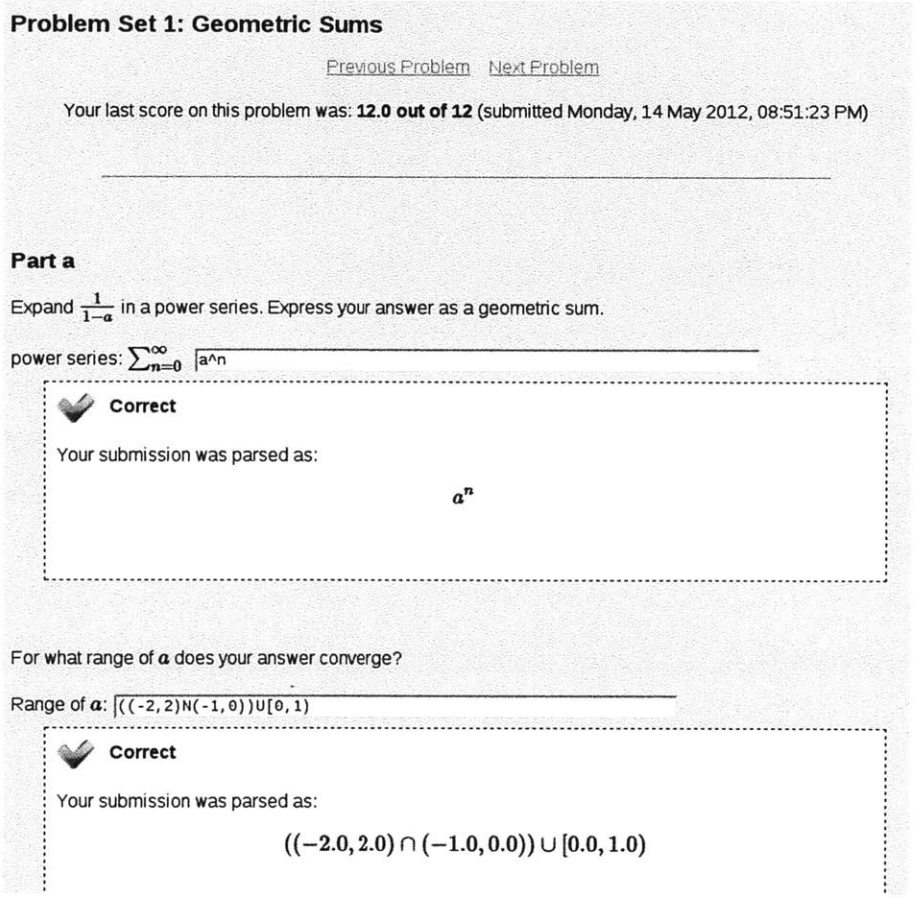


Figure 3-1: Screenshot showing CAT-SOOP's display of a simple symbolic math problem involving multiple parts.

3.1.1 Testing

The procedure for testing correctness of symbolic expressions has gone through several iterations. At first, CAT-SOOP made use of a symbolic math library for correctness checking. However, this approach was found to be lacking, particularly when checking complicated expressions. For example, checks involving complex exponentials or trigonometric functions tended to eat up a lot of CPU time (and could possible enter infinite recursions, forcing a restart of the server), and were not always accurate[2].

Because of these limitations, and the general difficulty of symbolic equivalence checking, CAT-SOOP currently does all its correctness checking numerically, which has proven in practice to be very efficient and accurate when compared against the symbolic approaches used before. The checking process unfolds as follows:

1. The given submission and solution are both parsed down into Python AST's[3].
2. Each variable that appears in at least one of the two expressions is assigned a numerical value (a random complex number within a certain range)[4].
3. Each AST is evaluated in the Python environment containing the variable bindings created in step 2.
4. These numbers are compared to one another; if they are within a certain threshold of one another, they are assumed to be equivalent expressions.

3.1.1.1 Errors in Checking

This method is not guaranteed to produce correct assessments, and both false positives (marking incorrect submissions as correct) and false negatives (marking correct solutions as incorrect) are possible.

[2]These flaws were responsible for some student frustration early on in *6.003*, when this checking scheme was still in use.

[3]It is worth noting here that, while this step relies on expressions being specified using Pythonic syntax, it is certainly possible to allow input languages other than Python, through the use of pre-processors which translate from the desired input language into Python.

[4]Currently, four variable names are reserved, and assumed to have special meaning: `j`, `e`, `abs`, and `sqrt`. If these variables appear within an expression, they are not assigned random values, but are interpreted as the imaginary unit, the base of the natural logarithm, the absolute value function, and the square root function, respectively.

Of the two types of errors, false positives are more likely, and could occur in the case where the randomly-generated numbers happen to cause the evaluation of the incorrect submission to be close enough to the evaluation of the correct solution. In practice, this rarely occurs with a sufficiently wide distribution over values which variables can take, even with threshold values as forgiving as 10^{-4}, and can be guarded against by running the above procedure n times, and only marking solutions as correct which pass all n tests (the false positive rate decays exponentially with n).

False negatives are also technically possible, but are extremely unlikely (even compared to false positives), to the extent that they can be largely ignored. Since the checker uses the same initial values for each variable, the only apparent way that a correct submission's evaluated value can diverge from that of the solution is through rounding error. While it is technically possible for this type of divergence to happen (particularly with a small enough threshold value), it is not a practical concern[5].

3.1.2 Feedback

Currently, the symbolic math system provides very limited feedback. The only type of feedback currently offered is a LaTeX representation of the user's input (see figure 3-1), which is useful for catching entry errors, but not terribly useful for catching conceptual errors.

3.1.3 Looking Forward

One idea for improving the feedback generated about students' submissions to symbolic math questions is to use solution-specific feedback, wherein common incorrect solutions to a problem are collected, and solution-specific canned responses are displayed to students whose answer takes one of those forms. The CyberTutor[17], an automatic tutor for introductory physics, uses this idea of feedback, and also offers feedback if the student's solution contains a variable not present in the solution, or

[5]In fact, tests involving exponentiation, as well as repeated multiplication and division, to try to introduce rounding error were never able to introduce enough error to create a false negative (with a threshold of 10^{-9}) without first running into limitations in Python's parser, or overflow errors.

vice versa (e.g., "the solution does not depend on x").

The CyberTutor also makes use of a type of proactive feedback through hints. Students are presented with a variety of hints, which are basically steps leading up to the solution. The student may ignore the hints, but if he gets stuck, he may open a hint, which could potentially push him in the right direction. An internal report by Warnakulasooriya and Pritchard[22] suggests that these hints are beneficial.

Another idea would be to systematically apply deformations to the AST which results from parsing down a submitted expression, to see if the solution can be reached; trees could be deformed, for example, by replacing nodes representing trigonometric functions with other trigonometric functions, or by negating nodes representing numbers or variables. If any combination of these deformations (and, potentially, other, more complex deformations) results in a tree that is equivalent to the solution, then targeted feedback can be given (e.g., "check your signs" if a negation caused the submission to become correct).

3.2 Ranges

In addition to checking symbolic expressions, CAT-SOOP is able to check numerical ranges. These questions are often follow-ups to symbolic expression questions, as can be seen in figure 3-1.

Appendix A (section A.1.1) contains the full source-code listing for `Range.py`, which is responsible for handling ranges in CAT-SOOP.

3.2.1 Testing

As with the symbolic expression checker, the range checker has gone through a number of changes since it was first used. Initially, input was given as a Pythonic boolean expression (for example, $|x| = 2$ could be specified as `(abs(x) == 2)`, or as `(x == -2 or x == 2)`, among other possibilities). This syntax proved tedious, however, for people with little or no programming background, to whom it felt like an unnatural way to represent ranges.

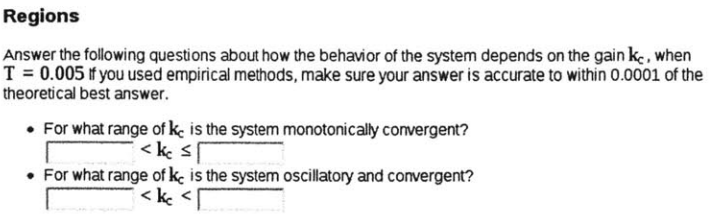


Figure 3-2: Screenshot showing range checking in tutor2, which is similar to a previous version of CAT-SOOP's range checking. Answers are given as two numbers: a lower bound, and an upper bound.

In this original scheme, checking was accomplished by randomly sampling a large number of points over some specified range, and checking whether each of those values of the variable in question caused the solution and the submission to resolve to the same answer (either `True` or `False`). If all of the points resulting in the submission and the solution resolving the same answer, then the submission was marked as correct. If they did not match, then the submission was marked as incorrect.

Obviously, this approach is not perfect; as with the method described for checking expressions, it has the potential to generate false positives (in the sense that it may mark incorrect submissions as correct), but will not mark any correct submissions as incorrect. Despite its inelegance, this approach has proven to do an adequate job of assessing student submissions in practice, and increasing the number of sampled points are tested would increase the accuracy of the checker in general.

The next iteration of the range checker required two numerical inputs per range: one for a lower bound, and one for an upper bound; a similar method is used in tutor2, as can be seen in figure 3-2. The benefit with this method was that checking was straightforward. However, phrasing questions in this manner limited the types of ranges which could be specified and the freedom of the instructors to write arbitrary problems.

Currently, the range checker uses the same testing methodology as the original Pythonic range specification, but also checks the boundaries of each region specified in either the solution or the submission. What has changed is the language used to specify ranges. Currently, the checker accepts input in a simple language designed

for the sole purpose of representing regions of the number line. A single region is represented in a typical fashion: as an ordered pair delimited by brackets, where a round bracket implies that a boundary is exclusive, and a square bracket implies that a boundary is inclusive; for example, `(0,3]` includes all positive real numbers x such that $0 < x \leq 3$. Positive and negative infinity are specified as `INF` and `-INF`, respectively.

These regions can be combined through the use of two operators: `N`, which represents an intersection ($\cap$), and `U`, which represents a union ($\cup$).

This last method is CAT-SOOP's current method of choice, though from examining these three schemes, it should be apparent that each has its own strengths and weaknesses. Depending on the context and the specific question being asked, any of these three options might be favorable.

3.2.2 Feedback

Similarly to symbolic expressions, the only feedback CAT-SOOP currently gives about a student's submission, aside from whether it is correct, is a LaTeX representation (see figure 3-1) of the submission. Once again, while this is useful for detecting entry errors, it offers little in the way of conceptual feedback.

The representation into which ranges are parsed is not as rich as an AST, and so, unfortunately, many of the interesting ways to improve feedback for expressions simply do not translate to ranges.

Chapter 4

Evaluating Computer Programs

One of CAT-SOOP's primary objectives is to automate the assessment of student-submitted computer programs. Because CAT-SOOP was designed for use at MIT, and Python is the language of choice in MIT's undergraduate curriculum, CAT-SOOP is currently only capable of assessing programs written in the Python programming language; despite this, the methods described in this chapter and the next will hopefully prove, at least to some extent, generally applicable, and extensible to other programming languages.

4.1 Subset of Python

CAT-SOOP's current means of assessing and providing feedback on students' submissions to programming exercises consists of a number of components, each of which places some constraints on the subset of the Python language which can be successfully and completely assessed.

The core testing system, which is built into the CAT-SOOP system, allows for almost the complete Python 2.7 language, with the exception of certain blacklisted statements (see section 4.2.1). However, the myriad components of the Detective add-

on (described in the following chapter) create additional, more severe constraints[1].

Explicitly allowed in the subset are:

- Booleans, Integers, Longs, Floats, and Complex Numbers
- Lists and Tuples
- Dictionaries
- For and While Loops
- Conditional Statements
- User-Defined Functions

Explicitly disallowed in the subset are:

- Multiple Assignment
- File Handling
- Yield Statements and Generators
- Imports
- Sets
- try/except/finally
- In-line conditional statements
- Slicing

Because the system really does consist of several disjoint pieces, the effects of using some of the above statements may be more benign than others.

[1]The aim here is to create a rich subset of the Python programming language, while still keeping it simple enough that meaningful feedback can be generated. Ideally, CAT-SOOP and the Detective will eventually be able to allow a more complete subset of Python. If the additional feedback afforded by the Detective is not a concern, the core system can still be used, which is capable of checking a much more complete subset of the language; in this case, the allow/deny lists above may be ignored.

4.2 Testing

Checking arbitrary programs for correctness in an absolute sense is an extremely difficult task, and so CAT-SOOP falls back on a method commonly used in automatic programming tutors: test cases. In particular, the code checking in CAT-SOOP is largely based off of similar systems used in the xTutor and tutor2 automatic tutors. Although details are ommitted here, appendix A (section A.1.2) contains the complete source-code listing for `pysandbox_subprocess.py`, which houses most of the code described in this section.

When a student's submission is checked for accuracy, it is run through a number of test cases, and the results of these executions are compared against the results of running a solution through the same test cases. Assuming an adequate battery of tests and a correct solution, then any submission which passes all the same test cases as the solution can be considered a correct submission.

Each programming question specifies a list of test cases, as well as (optionally) a block of code to be executed before running the submitted code (e.g., to define functions or variables which can be used in the student's submission). Each test case consists of an arbitrary number of statements, which ultimately set a variable `ans`, which is the end result of the test case. Once the student's code and the test case have been run, a string representation of `ans` is stored in a specific location. This process is repeated for each test case, and for the solution code.

Once all test cases have been run on both the student's code and the solution, the results of each test case are compared against one another. By default, the strings are compared against one another verbatim, but an arbitrary Python function may be used to compare the two (e.g., by converting each to a Python object, and then comparing those objects), which increases the variety and complexity of the checks which CAT-SOOP can perform.

4.2.1 Security

Allowing arbitrary pieces of code to run on a public web server is a dangerous prospect. CAT-SOOP's approach to avoiding executing dangerous code involves simply checking whether the submitted code contains any of a number of "blacklisted" statements, which are deemed dangerous either to the state of CAT-SOOP system, or of the machine on which it is running. This check is performed after stripping away all comments and whitespace (as well as the line continuation character \), so that formatting tricks cannot allow these statements to pass through.

Any code which contains any of these statements is not executed, and causes an e-mail to be sent to any user whose "Admin" bit (see section 2.3.4 for a discussion of permissions within CAT-SOOP) is set for the course in question; this e-mail contains the raw code submitted to the system, as well as the username of the individual who submitted the code.

To guard against infinite loops, Python's `resource` module is used to limit each test's running time to two seconds. Any code running for longer than two seconds is assumed to have entered an infinite loop.

While these measures certainly do not constitute a perfect means of sandboxing user-submitted code, they should provide a reasonable level of security nonetheless.

4.3 Feedback

The core system provides very simple feedback, letting the user know whether his code passed each of the test cases. However, Michael[14] suggests that students learning to solve problems benefit from feedback beyond a simple assessment of the correctness of their answer. Automatically generating meaningful feedback for arbitrary programs submitted by students is, in general, a very difficult problem, but one which CAT-SOOP seeks to address through the means of an add-on called the Detective.

The following chapter describes this system, which is aimed toward increasing students' understanding of how the state of a program evolves during a single execution, in detail.

Chapter 5

The Detective

CAT-SOOP focuses mainly on providing feedback about a single execution of a student's program. To this end, the Detective was developed. The Detective is a piece of software designed to provide detailed information about how the state of the execution environment changes as a program runs, as well as to provide insight into why and when errors occur during execution.

The use of run-time tracing in automatic tutors has been investigated by Striewe and Goedicke[21], who suggest that tracing in automatic tutors can be beneficial (in particular because it allows for easily generating certain valuable types of feedback which would be very difficult to generate without tracing), but also that there is much room for improvement in this regard. The goal of the Detective is to use run-time trace data, as well as syntactic information, to generate meaningful, concrete feedback about students' submissions to introductory programming exercises, and thereby increase students' power to solve programming exercises autonomously.

5.1 Tracing and Visualization

At the Detective's core is a visualization of the evolution of a program's environment as it is executed. This visualization is based on (and uses much of the original code for) Philip Guo's Online Python Tutor[1]. Guo's Tutor contains a tracer (`pg_logger`

[1] `http://people.csail.mit.edu/pgbovine/python/`

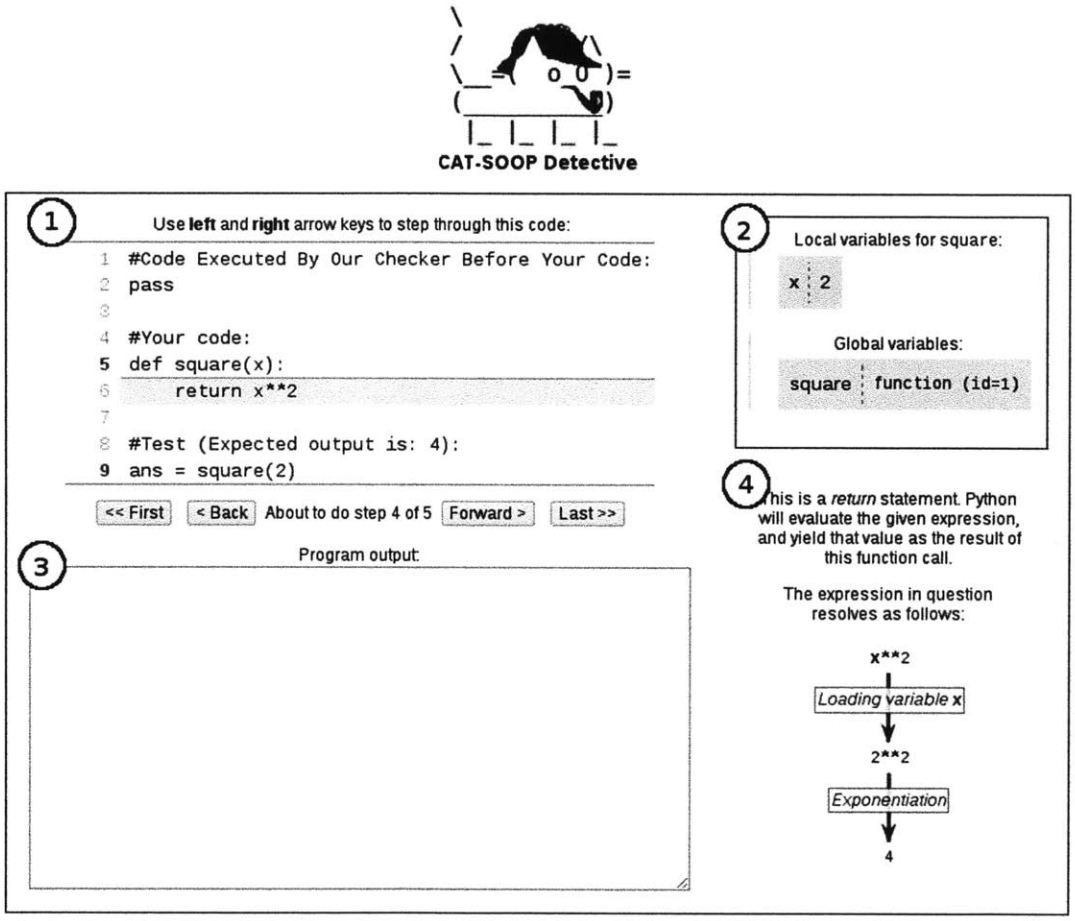


Figure 5-1: The user interface to the Detective, showing **(1)** the submitted code, **(2)** the current local and global variables, **(3)** the output from the program so far, **(4)** and an explanation of the current line's purpose.

Type of Error	Example Explanation
Name not defined	This message means that the program is trying to access a variable called `foo`. However, there is no such variable in the current scope. If this is the correct variable name, make sure it has been initialized first. If not, did you mean to use one of the following variables? `Foo`, `foO`
Object unsubscriptable	Grabbing a single element from a collection using square brackets (`[]`) is referred to as *subscripting*. This message means that the program is trying to subscript something that can't be subscripted (a `function`). If you intended to call this function, you should use parentheses instead of square brackets.
Object not callable	Executing the code stored within a function using round brackets (parentheses) is referred to as *calling* that function. This message means that the program is trying to call something that can't be called (a `list`). If you intended to index into this `list`, you should use square brackets (`[]`) instead of parentheses.
Operation not supported	This message means that the program is trying to combine two objects using an operator, but doesn't know how to do so. Specifically, this line is trying to combine an `int` and a `str` using the + operator, which is not supported.

Figure 5-2: The Detective's explanations of various types of run-time errors.

by name), which logs information about the evolution of local and global variables, as well as information relating to Python exceptions, over the course of a single execution of a program.

Guo's Tutor allows users to "step" through the program's execution line-by-line and observe how the program's internal state evolves.

The Detective uses a slightly-modified version of Guo's tracer (dubbed `hz_logger`), which includes syntactic information in the form of partial AST's, to augment this visualization with interpretations of error messages (as described in section 5.2), as well as expanded explanations of program behavior (section 5.4) and more finely-grained resolution information (section 5.4.1).

5.2 Error Analysis

While valuable to the expert programmer who has learned to interpret them, error messages present a challenge to the novice programmer. Most error messages are

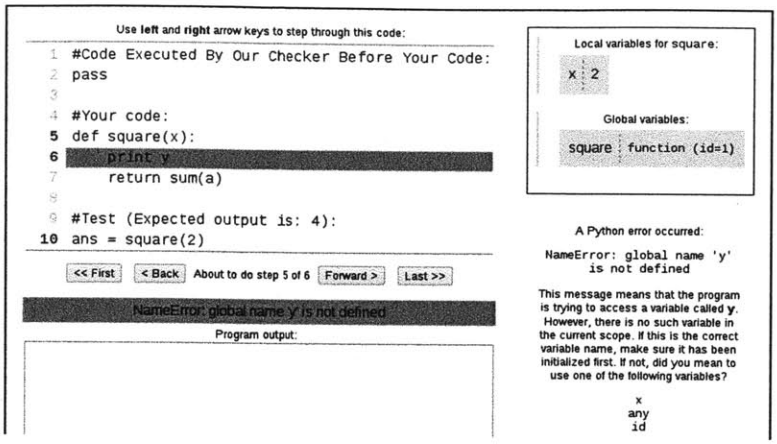


Figure 5-3: A screenshot of the Detective displaying an error message, along with an interpretation of that error message.

strangely worded, and even the more straightforward error messages are often buried in a pile of red text which can be intimidating, particularly to those just beginning with programming.

Many students have trouble interpreting these error messages, and thus require explanation as to what an error message means before they are able to go about trying to fix it.

The error analyzer tries to alleviate this problem by providing simple explanations of common error messages in plain English. The original error message generated by Python is still displayed, but is augmented by a simple explanation of what the error message means, in the hopes that students will begin to connect the simple explanation with the error message that Python generates, so that they will be better able to interpret such error messages when they are no longer working within the Detective.

The method by which these responses are generated is rather simplistic, but still provides meaningful, relevant interpretations of error messages; these messages are generated by considering the error message generated by Python, as well as the state of the local and global variables when the error occurred. Using this information, the Detective fills in an explanation template specific to the type of error encountered. Sample explanations for a few common types of errors can be seen in figure 5-2.

What follows is a description of several common errors students make, as well as the ways in which the Detective identifies and explains them. Some of these items are the Python equivalents of common Java mistakes enumerated by Hristova, et al[7] and Lang[12]; others on this list came from personal experience interacting with novice programmers, and from several semesters worth of xTutor's logfiles.

The complete source-code listing of `errors.py`, which contains the code for interpreting error messages, can be found in Appendix A, section A.2.1.

5.2.1 Common Run-time Errors

1. **Misspelled Variable Names** — Misspelling variable names is one common error. Even for an experienced programmer, a slip of the finger can result in a Python `NameError` stemming from a typographical error. For a novice, these errors are likely to be harder to understand, and to diagnose (for example, the idea that `Foo` and `foo` are different names in Python takes a little getting used to). When the Detective encounters a "name not defined" error, it displays a canned response explaining that the variable in question is not defined in the current scope. In addition, the system searches in the current scope (including Python's built-in variables and functions) for names that closely resemble the name the user typed in. These variable names are found by iterating through the current scope (+ built-ins), and computing the Damerau-Levenshtein distance[3] between the specified variable name, and each variable actually defined in the current scope. A list of those variables whose Damerau-Levenshtein distance to the specified variable name is less than or equal to two is displayed back to the user, as can be seen in figure 5-3.

2. **Incorrect Choice of Braces** — Novices will often confuse square brackets with parentheses, attempting to call a function with the syntax `foo[x]` or to index into a list with the syntax `foo(ix)`. The detective catches these types of errors by investigating certain `TypeErrors` (specifically those which are accompanied by an error message stating that a certain object is not subscriptable, or is not

callable). If a user tries, for example, to subscript a `function` object using square brackets, the Detective offers a suggestion to use parentheses instead of square brackets. Similarly, attempting to call a `list`, `tuple`, or `dict` object using parentheses will result in the Detective suggesting to use square brackets instead.

3. **Unsupported Operations** — Another common error is confusing types. This usually manifests itself when the user tried to perform some operation on an object, which its type forbids. One common error of this kind is attempting to add together two objects of differing types (e.g., `24 + '2.0'`). This error can manifest itself as an "unsupported operand types" error message[2]. In this case, the Detective gives a canned response, with some information injected about this specific instance of the error message.

4. **Index Out of Range** — When just starting with programming, most people are used to counting from one, and so Python's zero-indexing of lists and tuples can be a stumbling point, even if it is not a conceptually difficult concept. The Detective responds to "index out of range" errors with a simple canned response, a reminder about counting from zero and valid indices.

5.2.2 Pitfalls

The Detective's error checking goes beyond reporting actual exceptions to warn users about common mistakes in Python which don't necessarily cause exceptions, but might lead to unexpected behavior. Because they don't necessarily cause Python exceptions to occur, these cases are handled separately from other error reporting. Python has a few of these "pitfalls" (to borrow terminology from Lang), some of which are enumerated below:

[2]These errors can also manifest themselves in other ways, with a wide variety of error messages, depending on which of the operands is given first. Additionally, `AttributeErrors` might arise from misunderstanding types. As a proof-of-concept, the Detective currently only explains those errors of this kind which give rise to this specific error message; however, it could easily be extended to account for those other cases.

1. **Exponentiation Syntax** — Novices with backgrounds in mathematics, as well as experiences programmers who are new to Python's syntax, tend to want to use a caret (^) to denote exponentiation, when in Python this represents bit-wise exclusive or (XOR). Since students are more likely to be called to use exponentiation than XOR in introductory programming exercises, the Detective gives a warning whenever this operator is used. An example of such a warning is:

   This line contains a caret (^), which represents a bitwise XOR operation. If you intended to use exponentiation, use two asterisks (**) instead.

2. **Overwriting or Hiding Built-in with Variable** — One subtle pitfall is the possibility of overwriting or hiding built-in objects in Python through assignment statements. Many built-ins have names which are desirable for variable names; in particular, the type names (among them `list`, `str`, `dict`), as well as `max` and `min`, tend to be overwritten frequently, and this is a common occurrance for other built-in variables as well. Any time the Detective encounters an assignment statement which gives a warning whenever an assignment overwrites or hides a built-in variable. An example of such a warning is:

   This line contains an assignment to a variable named **int**. *However,* **int** *is also the name of an object built in to Python. This assignment will "hide" the built-in object, so that it will not be accessible from within this function.*

Additional pitfalls were considered, including leading zeros on integers (which are interpreted as octal numbers in Python), and using `&` and `|` instead of `and` and `or` in boolean expressions. However, both of these concepts are difficult to explain concisely without assuming a background in mathematics or computer science, and so are not considered in the current version of the Detective.

5.3 Syntax Errors

Syntax errors in Python are particularly hard to diagnose and fix. Novices tend to make a lot of mistakes when programming, which cause Python to be unable to execute their code. Many novice errors are greeted with a familiar (and really unhelpful) message: `SyntaxError: invalid syntax`. Because of this, novices tend to spend a lot of time staring at code that will not run, trying to figure out where their errors lie.

Thus, an ideal automatic tutor would be able to provide insight into why syntax errors, in addition to run-time errors, occur. However, the problem of identifying the causes of syntax errors is intrinsically more difficult than analyzing run-time errors, if for no other reason than that syntax errors disallow the possibility of investigating Abstract Syntax Trees, forcing consideration instead back to the level of textual source code.

As it currently stands, the Detective does not make any attempt to analyze or explain syntax errors, although such analysis is certainly a goal for future versions, as the potential gains are substantial.

5.4 Statement Explanation

In addition to the providing interpretations of error messages, the Detective also incorporates a system which attempts to explain what each line of a student's program is doing as it executes. This system, hereafter referred to as the explainer, is very simplistic, but may provide some clarity (or at least a useful reminder) as to what a given line will actually do when executed; this information is likely most useful for people just getting started with programming.

The explainer basically maps AST node types to canned explanations, with some small variation depending on the structure of the AST rooted at the node in question. For example, a `return` statement with no return value specified will generate an explanation similar—but not identical—to a `return` statement with a return value

specified. Announcements are also made when entering (via a function call) or exiting (via a `return` statement or reaching the end of a function's definition) a function. This scheme is admittedly simplistic, but should at least serve as a proof-of-concept for future systems. Table 5-4 shows examples of generated explanations for several types of Python statements.

When appropriate, these simple explanations are augmented by more finely-grained information about how a given expression resolves; these messages, and the method by which they are generated, are described in detail in the following section.

5.4.1 (Pseudo-) Instruction-Level Resolution

When a student's program begins producing unexpected results, he is often pointed to a specific line of code where the error occurred, but from there, he is left on his own to figure out where, specifically, his error lies. Often, a line of code consists of several instructions; because of this, it can be difficult to determine when during that line's execution the program started to deviate from what the programmer intended. This is particularly true in cases when a program runs successfully (in the sense that it runs through to completion without generating a Python error) but nonetheless produces incorrect results.

For this reason, the Detective seeks to provide finely-grained information about how a given expression resolves. Other program visualizations (such as jEliot[16]) accomplish similar goals by investigating a program's bytecode. However, a quick inspection of Python's compiler showed that it makes some optimizations at compile time that could prevent the Detective from giving a complete picture of how a line resolves[3].

As an alternative, the Detective uses a system which resolves Abstract Syntax Trees step-by-step. This method I call (pseudo-) Instruction-Level Resolution (hereafter pILR). The underlying idea is that by resolving an AST step-by-step in a sys-

[3]While the only optimization I directly observed involved pre-computing additions (e.g., 2+3 compiled to `LOAD_CONST (5)`), seeing this early on made me wary of using bytecode, which might make use of other optimizations that could potentially impede the Detective's ability to show every step of a resolution.

Type of AST Node	Example Explanation
`Assign`	This is an *assignment* statement. Python will evaluate the expression on the right-hand side of the equals sign, and will store the resulting value in variable `x`.
`Break`	This is a *break* statement. If it is given inside of a loop, this statement will cause Python to jump outside the loop, skipping the rest of the code block for this iteration and all subsequent iterations. If given outside of a loop, this statement will cause an error.
`Continue`	This is a *continue* statement. If it is given inside of a loop, this statement will cause Python to jump to the top of the loop, skipping the rest of the code block for this iteration. If given outside of a loop, this statement will cause an error.
`For`	This is a *for* loop. Python will run the given code block once for each element in `foo`, each time setting a variable `i` equal to the next element in `foo`.
`FunctionDef`	This is a *function definition* statement. Python will store this function in variable `foo` so that it may be called later.
`If`	This is an *if* statement. Python will evaluate the given expression. If it evaluates to `True`, Python will jump to line x; if it evaluates to `False`, Python will jump instead to line y
`Pass`	This is a *pass* statement, which tells Python to do nothing.
`Print`	This is a *print* statement. Python will evaluate the given expression, and display it to the console.
`Return`	This is a *return* statement. Since no expression was given, Python will yield `None` as the result of this function call.
`While`	This is a *while* loop. Python will evaluate the given expression. If it evaluates to `True`, Python will jump to line x, execute the code in that block, and return here to check the expression again. If it instead evaluates to `False`, Python will skip this code block altogether.

Figure 5-4: The Detective's explanations of supported types of Python statements.

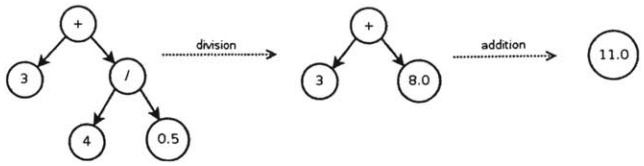


Figure 5-5: pILR trace of `3 + 4 / 0.5`, depicted as partial AST's

tematic manner, one can mimic the process by which Python would evaluate an expression, and explore the evolution of that expression as it resolves. Figure 5-5 shows an example of a simple pILR trace.

Each type of AST node[4] resolves in a specific way, and provides a specific message stating what is being done as it resolves (for example, a `Name` node, which represents loading a variable, is accompanied by a message "Loading variable x."). The specifics of each type's resolution, which are naturally motivated by the ways in which Python evaluates different types of expressions, will not be discussed here in detail, but Appendix A (section A.2.5) contains a complete source-code listing for `resolution.py`, which contains the pILR code.

As mentioned before, the main motivation in developing the pILR system was to provide information to students about when, specifically, errors occur during the resolution of a line of code. Thus, the pILR scheme must have a means of dealing with Python errors which occur mid-line, and still be able to provide a partial trace when these types of errors occur. To this end, the pILR system makes use of a special `Error` node during resolution. In the case where an error occurs when resolving a sub-tree, the error node replaces whatever node would have resulted in the case of a successful resolution. Different types of AST nodes check for errors in subtree resolution at different times, but the ultimate end result is that the `Error` node propagates up the tree; this may preclude the resolution of sibling nodes, but will not interfere with those resolutions which were completed successfully before the error occurred. Figure 5-6 shows an example of this behavior in a simple context.

Not only is pILR capable of creating finely-grained traces of the resolution of a

[4]Currently supported are `BinOp`, `BoolOp`, `Compare`, `Dict`, `List`, `Name`, `Num`, `Str`, `Subscript`, `Tuple`, and `UnaryOp`.

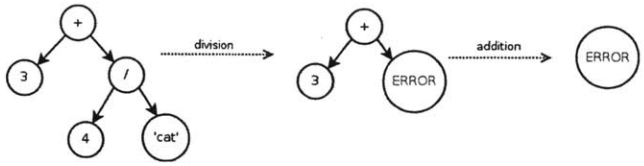


Figure 5-6: pILR trace of `3 + 4 / 'cat'`, depicted as partial AST's, and demonstrating the propagation of an `ERROR` node.

number of different Python expressions, but is seems to have an additional benefit over creating these traces from compiled Python bytecode: pILR maintains, at all times, an explicit representation of the current state of the resolution, in the form of a Python AST. This representation is currently used to create the Detective's visualization of pILR traces; the Detective walks these partially-resolved AST's to create Python code which, when parsed, would generate the AST in question; this Python code is then used in the Detective's visualization.

The Detective uses the jsPlumb JavaScript library[5] to connect the partially-resolved AST's, and to give brief descriptions of what each step in the trace is doing; figure 5-7 shows the resolution of a more complicated example as it appears within the Detective, from a student's (correct) submission to a question asking for a program to compute the roots of a quadratic expression.

5.5 Connecting with CAT-SOOP

Because the Detective exists as a stand-alone web application, some care had to be given to connecting it with CAT-SOOP in a reasonable way.

The connection is made through a modified version of the Python Code question type[6], called `PythonCodeViz`. When a `PythonCodeViz` question is submitted, the submission is checked for correctness in the usual manner, as described in section 4.2. In addition, several versions of the code (one for each test case) are sent via HTTP POST request to a CGI front-end to `hz_logger`, which generates a JSON

[5] `http://jsplumb.org/jquery/demo.html`

[6] see chapter 4 for a discussion of this question type, and section 2.3.1 for a general discussion of question types within CAT-SOOP

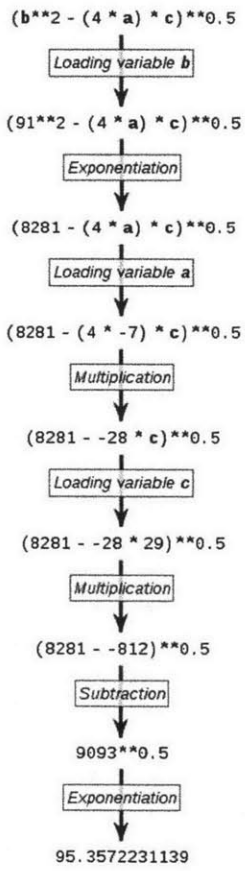


Figure 5-7: The pILR trace of calculating a determinant, as visualized in the Detective.

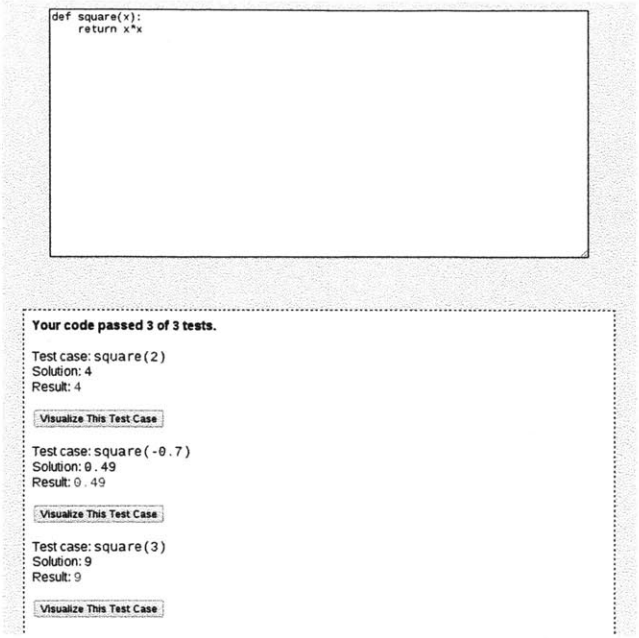


Figure 5-8: Screenshot showing a student's response to a question and the associated feedback, including buttons which open instances of the Detective.

object representing each program execution's trace. These JSON representations are hidden in the HTML source of the page that displays the results of the checking.

In addition to the normal feedback he receives about his program's feedback (which test cases his code passes, as well as any solution-specific feedback as described in section 4.3), the student is presented with buttons which offer him the ability to visualize any of the given test cases using the Detective. When one of these buttons is pressed, the corresponding test case's trace is pushed into a hidden form, which is submitted to open a new instance of the Detective for visualizing that test case's execution. An example of this interface is shown in figure 5-8.

5.6 Looking Ahead

In its current form, the Detective plays the role of a disseminator of knowledge, and as an interpreter of Python's internal state as well as the messages the Python interpreter generates. Missing, however, from this setup is a sense of interactivity. As it currently stands, a student's interaction with the Detective is limited to passively absorbing the

explanations and interpretations the Detective provides. Looking toward the future, there is potential to improve the interactivity of students' use of the Detective.

Hundhausen, et al[8] suggest that the type and quality of a user's interaction with a software visualization is more important than the content of the visualization itself. This supports the principle of active learning, whose techniques have proven effective[15] across disciplines and degrees of mastery. The ideas that follow are centered around actively engaging the user through the detective, based on the fact that such engagement has proven effective over the years.

Inspired by Ko and Myers[10], one idea is to incorporate questions and answers into the Detective, allowing users to ask questions about different elements in the visualization and receive automatically-generated answers in response. In this same vein, Myller[18] suggests that incorporating "prediction"-type questions into a software visualization can increase the benefit students receive from interacting with that visualization, and that this task can be automated.

Certain types of questions (e.g., "what does this line do?", "how does this expression resolve?", and "what does this error message mean?") would be relatively easy to incorporate into the Detective in its current form, as the answers to these questions are already generated by the explainer, the pILR system, and the error analyzer, respectively. Answering additional types of questions, such as "why did variable x have value y at this time?" seems feasible, by searching backward in time through execution trace.

The inclusion of both predictive and summative questions has the potential to greatly increase the feeling of interactivity elicited from the Detective; this is desirable in that these questions could force the student to think about the issues with his program (thus potentially realizing them on his own) before being presented with information about it.

It is also worth noting that, in its current form, the Detective has no knowledge whatsoever of the problem the student is trying to solve, nor of the instructor's solution to that problem. If this extra knowledge were to be incorporated into the Detective, it is easy to imagine comparing students' submissions to instructors' solutions

to provide additional information about relative complexity or style. For example, the cyclomatic complexity[13] or running time of the student's code might be compared against the solution to give students an idea not only of whether the submitted code is correct, but also about how efficient it is.

Beyond even this, one can imagine tailoring the Detective's responses to individuals, based on an estimate of each student's level of understanding of various programming practices and syntactic structures. In its current form, the Detective generates feedback that is almost exclusively geared toward novices, but the argument could be made that an ideal automatic tutor would be able to cater to a broader audience.

It is well-established that novices and experts in a given domain view problems in that domain differently; at the very least, experts tend to notice more patterns and abstractions not noticed by novices, and have a deeper understanding of how these patterns and abstractions relate to the problem being solved[19]. Thus, it makes sense that an ideal automatic tutor would (much like a human tutor) use different language and examples to explain concepts to students with various levels of understanding and ability.

Implicitly, the Detective assumes that its users are very new to programming as a discipline, using text to describe how statements are interpreted at a very low level, but not providing insight above that level. It is feasible that the templates the Detective uses to generate explanations of error messages and statements could be modified based on an estimate of an individual's understanding of various concepts. Beck, et al[1] describe a method for gathering such an estimate from students' responses to various exercises in an intelligent tutoring system for middle-school-level mathematics, which could potentially be extended to the domain of computer programming.

Chapter 6

Conclusions and Future Work

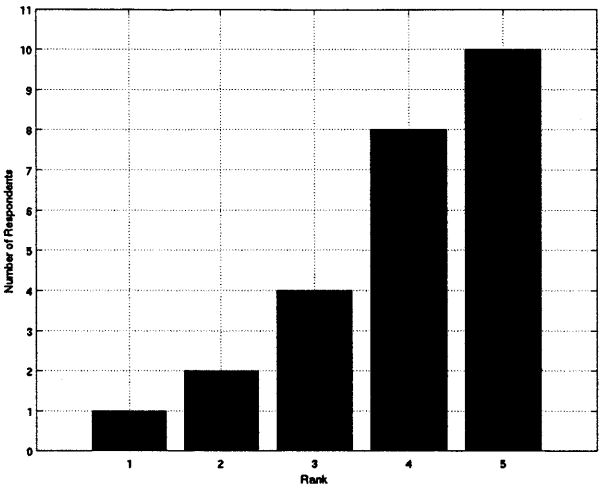
The CAT-SOOP system has proven to be a success in its initial pilot test, and early surveys have provided insight into valuable areas of future work.

Results from *6.003*'s end-of-term survey for fall 2011 suggest that, in general, students enjoyed using CAT-SOOP to submit their homework assignments, and informal qualitative feedback corroborates with this. Figure 6-1 contains a graph of the raw data collected from this survey.

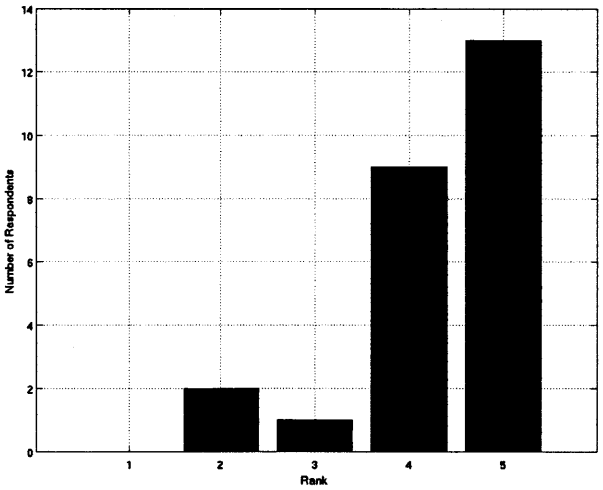
Despite the fact that feedback was generally positive, some of the most interesting feedback received took the form of negative comments. Quoting from the survey results:

- "The tutor encourages obsession over the correct answer. Due to lack of feedback about why an answer was wrong, you don't learn anything better than from just handing in paper."
- "The tutor should give more feedback, such as ... being off by a constant."
- "Try looking into using it differently, though, so students don't use it as a crutch."

The comments suggest that, for these types of systems to provide maximal benefit over paper assignments, the feedback they provide must not only be immediate, but most go beyond assessment of a submission's correctness. In addition, the comments



(a) "I liked the 6.003 tutor."



(b) "The most important feature of the 6.003 tutor is that it provides immediate feedback."

Figure 6-1: Students' responses to end-of term survey questions relating to CAT-SOOP for *6.003*, fall term 2011. Users were asked to rank their degree of agreement with the above statements on a scale from 1 (total disagreement) to 5 (total agreement), with 3 as a neutral point. A total of 25 data points were collected for each question.

also seem to suggest that this limited feedback may result in the students themselves focusing more on correctness than on conceptual understanding[1]. Thus, it certainly seems that a valuable line of future research in automatic tutoring lies in investigating additional forms of conceptual feedback, as well as the means by which they may be automatically generated from student submissions (chapter 3 discusses a few such possibilities, and many more certainly exist).

Unfortunately, the Detective has not been rigorously tested[2]; however, its unique type of feedback (objective data about the program's exeuction, augmented by interpretations of common Python statements and error messages, garnered and interepreted through relatively simple means) provides an interesting alternative to other methods of feedback currently being investigated. Thus, future plans include thorough testing of the Detective, as well as incorporating some of the additional feedback measures discussed in chapter 5.

While it still remains to be seen whether, and to what extent, CAT-SOOP and the Detective will prove beneficial to students in the future, early results show that students in *6.003* saw it as helpful, and suggest that this benefit could be carried over to *6.01*, or other courses, with relative ease. In addition, although it has not been thoroughly tested, the Detective provides a proof-of-concept for an interesting integration between run-time traces and automatic tutors, and suggests that more research along these lines may yield positive results.

[1]Indeed, through my experience with 6.01, I have noticed (in some students) a tendency to focus on attaining full marks on online problems, with little regard for the underlying concepts. Often this limited thinking manifests itself as an inability on the part of the student to explain the process by which he solved the problem, and an inability to abstract important concepts away from a particular problem and apply them in another context. Whether this is simply natural behavior on a student's part, or whether automatic tutors (and the immediate feedback they provide) contribute to this attitude, remains to be seen.

[2]Nor has the checking of Python code within CAT-SOOP, but since tutor2 and CAT-SOOP share essentially the same checking code for programming exercises, it is likely just fine.

Appendix A

Source Code Listings

A.1 CAT-SOOP

A.1.1 expressions_ast.py

```
1  # expressions_ast.py
2  # new module for checking symbolic expressions in CAT-SOOP/tutor2
3  #
4  # 2 march 2012, adam j hartz <hartz@alum.mit.edu>
5
6  import ast # Python's parser
7  import math,cmath
8  import random
9
10 def parse_expr(string):
11     """
12     Parse down an expression into a Python AST
13     """
14     node = ast.parse(string)
15     return node.body[0].value # ast parser gives us a 'module'; first object in it is the expression
16
17 def compile_ast(tree):
18     """
19     Compile an AST tree into a Python code object to be run
20     """
21     expr = ast.Expression(tree)
22     expr.lineno = 1
23     expr.col_offset = 0
24     return compile(expr,"<CAT-SOOP>", "eval")
25
26 def get_all_names(tree):
27     """
28     Given an AST, return a list of all variable names contained within it.
29     For now, ignores attributes, slices, etc.
30     """
31     if isinstance(tree,ast.Name):
32         return [tree.id]
33     out = []
```

```
34      for child in ast.iter_child_nodes(tree):
35          out.extend(get_all_names(child))
36      return out
37
38  def get_var_values(names):
39      """
40      Assign random values to each variable name the list passed in.
41
42      Uses complex type for all numbers.  Always give the following values:
43          'j' is complex(0,1)
44          'e' is math.e
45          'sqrt' is cmath.sqrt function
46          'abs' is built-in absolute value function
47      """
48      out = dict([(name,complex(random.uniform(-20,20))) for name in names])
49      out.update({'j':complex(0,1),'e':math.e,'sqrt':cmath.sqrt,'abs':abs}) # reserved names
50      return out
51
52  def get_numerical_value(tree,varcache):
53      #varcache is a dictionary mapping variable names to numerical value
54      t = compile_ast(tree)
55      return eval(t,varcache)
56
57  def check(submission, solution, threshold=1e-4):
58      """
59      Compare a student's submission to a solution by parsing down into an
60      AST, generating numerical values for each variable, and evaluating the
61      AST
62
63      returns a dictionary with two keys:
64          'ok' maps to a Boolean, whether the two submissions match
65          'msg' maps to a message to be displayed back to the user
66      """
67      try:
68          p = parse_expr(submission)
69      except:
70          return {'ok':False,'msg':'This expression contains a syntax error'}
71      pa = parse_expr(solution)
72      vars = {}
73      vars.update(get_var_values(get_all_names(p)))
74      vars.update(get_var_values(get_all_names(pa)))
75      l = get_latex(p)
76      v = get_numerical_value(p,vars)
77      va = get_numerical_value(pa,vars)
78      ok = abs(v-va) < threshold
79      msg = "Your expression was parsed as:<br><dmath>%s</dmath>" % l
80      return {'ok':ok,'msg':msg}
81
82  def check_n(n,submission,solution,threshold=1e-4):
83      tests = [check(submission,solution,threshold,verbose) for i in xrange(n)]
84      return {'ok': all([i['ok'] for i in tests]), 'msg':tests[0]['msg']}
85
86
87
88  ####
89  #AST-to-LaTeX
90  # Most of this code is by Geoff Reedy (http://stackoverflow.com/users/166955/geoff-reedy)
91  # Found at http://stackoverflow.com/questions/3867028/converting-a-python-numeric-expression-to-latex
92  ####
93
94  import ast
```

```
95
96  #Greek letters: input-to-output mapping
97
98  GREEK_LETTERS = ['alpha', 'beta', 'gamma', 'delta', 'epsilon', 'zeta', 'eta', 'theta', 'iota',
99                   'kappa', 'lambda', 'mu', 'nu', 'xi', 'omicron', 'pi', 'rho', 'sigma', 'tau',
100                  'upsilon', 'phi', 'chi', 'psi', 'omega']
101 GREEK_DICT = {}
102 for i in GREEK_LETTERS:
103     GREEK_DICT[i] = "\\%s" % i
104     GREEK_DICT[i.upper()] = "\\%s" % i.title()
105
106
107 class LatexVisitor(ast.NodeVisitor):
108
109     def prec(self, n):
110         return getattr(self, 'prec_'+n.__class__.__name__, getattr(self, 'generic_prec'))(n)
111
112     def visit_Call(self, n):
113         func = self.visit(n.func)
114         args = ', '.join(map(self.visit, n.args))
115         if func == 'sqrt':
116             return r'\sqrt{%s}' % args
117         elif func == 'abs':
118             return r'\left| %s \right|'
119         else:
120             return r'\operatorname{%s}\left(%s\right)' % (func, args)
121
122     def prec_Call(self, n):
123         return 1000
124
125     def visit_Name(self, n):
126         i = n.id
127         s = i.split("_")
128         if len(s) > 2:
129             return "".join(s)
130         elif len(s) == 2:
131             if len(s[1]) > 1 or len(s[1]) == 0:
132                 return "".join(s)
133             else:
134                 return "%s_%s" % (GREEK_DICT.get(s[0],s[0]),s[1])
135         else:
136             return GREEK_DICT.get(i,i)
137
138     def prec_Name(self, n):
139         return 1000
140
141     def visit_UnaryOp(self, n):
142         if self.prec(n.op) > self.prec(n.operand):
143             return r'%s \left(%s\right)' % (self.visit(n.op), self.visit(n.operand))
144         else:
145             return r'%s %s' % (self.visit(n.op), self.visit(n.operand))
146
147     def prec_UnaryOp(self, n):
148         return self.prec(n.op)
149
150     def visit_BinOp(self, n):
151         if self.prec(n.op) > self.prec(n.left):
152             left = r'\left(%s\right)' % self.visit(n.left)
153         else:
154             left = self.visit(n.left)
155         if self.prec(n.op) > self.prec(n.right):
```

```
156             right = r'\left(%s\right)' % self.visit(n.right)
157         else:
158             right = self.visit(n.right)
159         if isinstance(n.op, ast.Div):
160             try:
161                 l = get_numerical_value(n.left,{})
162                 r = get_numerical_value(n.right,{})
163             except: #this branch means there's a variable involved
164                 return r'\frac{%s}{%s}' % (self.visit(n.left), self.visit(n.right))
165             if isinstance(l,int) and isinstance(r,int): # if both ints, explicitly show floor division
166                 return r'\left\lfloor\frac{%s}{%s}\right\rfloor' % (self.visit(n.left), self.visit(n.right))
167             else:
168                 return r'\frac{%s}{%s}' % (self.visit(n.left), self.visit(n.right))
169         elif isinstance(n.op, ast.FloorDiv):
170             return r'\left\lfloor\frac{%s}{%s}\right\rfloor' % (self.visit(n.left), self.visit(n.right))
171         elif isinstance(n.op, ast.Pow):
172             return r'%s^{%s}' % (left, self.visit(n.right))
173         else:
174             return r'%s %s %s' % (left, self.visit(n.op), right)
175
176     def prec_BinOp(self, n):
177         return self.prec(n.op)
178
179     def visit_Sub(self, n):
180         return '-'
181
182     def prec_Sub(self, n):
183         return 300
184
185     def visit_Add(self, n):
186         return '+'
187
188     def prec_Add(self, n):
189         return 300
190
191     def visit_Mult(self, n):
192         return '\\cdot'
193
194     def prec_Mult(self, n):
195         return 400
196
197     def visit_Mod(self, n):
198         return '\\bmod'
199
200     def prec_Mod(self, n):
201         return 500
202
203     def prec_Pow(self, n):
204         return 700
205
206     def prec_Div(self, n):
207         return 400
208
209     def prec_FloorDiv(self, n):
210         return 400
211
212     def visit_LShift(self, n):
213         return '\\operatorname{shiftLeft}'
214
215     def visit_RShift(self, n):
216         return '\\operatorname{shiftRight}'
```

```
217
218     def visit_BitOr(self, n):
219         return '\\operatorname{or}'
220
221     def visit_BitXor(self, n):
222         return '\\operatorname{xor}'
223
224     def visit_BitAnd(self, n):
225         return '\\operatorname{and}'
226
227     def visit_Invert(self, n):
228         return '\\operatorname{invert}'
229
230     def prec_Invert(self, n):
231         return 800
232
233     def visit_Not(self, n):
234         return '\\neg'
235
236     def prec_Not(self, n):
237         return 800
238
239     def visit_UAdd(self, n):
240         return '+'
241
242     def prec_UAdd(self, n):
243         return 800
244
245     def visit_USub(self, n):
246         return '-'
247
248     def prec_USub(self, n):
249         return 800
250     def visit_Num(self, n):
251         return str(n.n)
252
253     def prec_Num(self, n):
254         return 1000
255
256     def generic_visit(self, n):
257         if isinstance(n, ast.AST):
258             return r'' % (n.__class__.__name__, ', '.join(map(self.visit, [getattr(n, f) for f in n._fields])))
259         else:
260             return str(n)
261
262     def generic_prec(self, n):
263         return 0
264
265 def get_latex(tree):
266     return LatexVisitor().visit(tree)
```

A.1.2 pysandbox_subprocess.py

```
#!/usr/bin/python
#
# File:    pysandbox_subprocess.py
# Date:    30-Aug-11
# Author: Adam Hartz <hartz@alum.mit.edu>


#------------------------------------------------------------------------
# run code in sandbox and return strings

import subprocess
import re
import resource
import os

DANGEROUS_CODES = ["mysqldb","_mysql","sqlalchemy","importos","fromosimport",\
                   "importsys","fromsysimport","open(","file.__init__",\
                   "code.__init__",".__subclasses__","subprocess","fork(","multiprocessing",\
                   "threading","builtins"]

def remove_comments(code):
    """
    Remove all comments from a piece of code
    """
    lines = code.splitlines()
    for lineno in xrange(len(lines)):
        line = lines[lineno]
        ix = line.find("#")
        if ix >= 0:
            lines[lineno] = line[:ix]
    return "\n".join([line for line in lines if line.strip()!=''])

def is_safe(code):
    """
    Rudimentary means of checking whether submitted code is an attempt to muck with the system
    """
    code = remove_comments(code).replace(" ","").replace("\t","")\
           .replace("\\","").replace("\n","")
    for c in DANGEROUS_CODES:
        if code.find(c) >= 0:
            return False
    return True

def mangle_code(code,argv):

    #if code contains blacklisted statement, don't run it
    if not is_safe(code):
        return code, False

    #otherwise, prepare code for execution

    # mangle code to change os.getenv(foo) to ENV[foo]
    code = re.sub('os\.getenv\(([a-z0-9\'\"]+)\)','ENV[\\1]',code)
    code = re.sub("os\.fdopen\(3,'w'\)",'log_output',code)

    # remove import os
    code = code.replace('import os','')

    # remove f.close()
```

```
60      code = code.replace('f.close()','')
61
62      # remove sys.exit(0)
63      code = code.replace('sys.exit(0)','')
64
65      # clean up CR's
66      code = code.replace('\r','')
67
68      head = "import sys\noldpath = sys.path\nsys.path = ['/usr/lib/python2.6','/home/tutor2/tutor/python_lib/
            lib601','/home/tutor2/tutor/python_lib']\n\n"
69      head += "from cStringIO import StringIO\nlog_output = StringIO()\n\n"
70      head += "ENV = %s\n\n" % repr(argv)
71
72      footer = "\n\nprint \"!LOGOUTPUT\"\n" # our magic keyword
73      footer += "print log_output.getvalue()\n" # values to compare
74      code = head + code + footer
75      return code, True
76
77  def setlimits():
78      """
79      Helper to set CPU time limit for check_code, so that infinite loops
80      in submitted code get caught instead of actually running forever.
81      """
82      resource.setrlimit(resource.RLIMIT_CPU, (2, 2))
83
84  def sandbox_run_code(code,argv):
85      """
86      Run code, returning stdout, stderr, and output_log.
87
88      argv should be a dict, giving the initial virtual environment.  We use it for
89      passing argument valies, ie argv1, argv2, ... to the code being run
90
91      """
92
93      (code, code_ok) = mangle_code(code,argv)
94
95      if not code_ok:
96          return('','BAD CODE - this will be logged','')
97
98
99      python = subprocess.Popen(["python"],stdin = subprocess.PIPE,\
100                                          stdout = subprocess.PIPE,\
101                                          stderr = subprocess.PIPE,\
102                                          preexec_fn = setlimits)
103     output = python.communicate(code)
104
105     out,err = output
106
107     n = out.split("!LOGOUTPUT") # separate output from variables we want to compare
108
109     if len(n) == 2: #should be this
110         out,log = n
111     elif len(n) == 1: #code didn't run to completion
112         if err.strip() == "":
113             err = "Your code did not run to completion, but no error message was returned."
114             err += "\nThis normally means that your code contains an infinite loop or otherwise took too long to
                    run."
115         log = ''
116     else: #someone is trying to game the system?
117         out = ''
118         log = ''
```

```
119             err = "BAD CODE - this will be logged"
120         if len(out) >= 500: #truncate long code output
121             out = out[:500]+"\n\n...OUTPUT TRUNCATED..."
122 
123         return out,err,log
```

A.1.3 Range.py

```
# range.py
# hartz 2011

from __future__ import division
import re
import sys
import random
from Question import Question

class Range(Question):
    name = "Range"
    author = "Adam Hartz"
    email = "hartz@mit.edu"
    version = "2.1"
    date = "29 December 2011"

    def checker(self,submit,solution,user,last_submit):
        try:
            sub = parse(submit)
            sol = parse(solution)
            msg = "Your submission was parsed as:<br />\[%s\]" % str(sub)
        except:
            return (0.0, ("Your submission could not be parsed:<br /><tt>%s</tt>" % submit, ), "Error", submit)
        ok = random_check_range(sub,sol) and check_key_nums(sub,sol)
        if ok == True:
            bigmsg = "Correct"
        else:
            bigmsg = "Incorrect"
        return (1.0*ok, (msg,), bigmsg, submit)

    def get_html_template(self):
        return """%%if LAST_SUBMIT != None:
<input type='text' size='60' name='%s' value='${LAST_SUBMIT}' />
%%else:
<input type='text' size='60' name='%s' value='%s' />
%%endif\n""" % (self.name,self.name,self.default)

def random_check_range(r1,r2,lo=-10000,hi=10000,num=int(1e5)):
    for i in xrange(num):
        check = random.uniform(lo,hi)
        if r1.contains(check) != r2.contains(check):
            return False
    return True

def check_key_nums(sub,sol):
    for check in get_interesting_points(sol).union(get_interesting_points(sub)):
        if sub.contains(check) != sol.contains(check):
            return False
    return True

def str_to_range(s):
    m = list(Interval.matcher.finditer(s.strip()))
    if m is None or len(m) == 0:
        return None
    g = m[0].groups()
    if g[1].strip() == "INF":
        left = float('inf')
    elif g[1].strip() == "-INF":
        left = float('-inf')
```

```
60      else:
61          l = ("1.0*%s" % g[1])
62          left = eval(l)
63      if g[2].strip() == "INF":
64          right = float('inf')
65      elif g[2].strip() == "-INF":
66          right = float('-inf')
67      else:
68          r = ("1.0*%s" % g[2])
69          right = eval(r)
70
71
72      il = g[0].strip() == '['
73      ir = g[3].strip() == ']'
74      return Interval(left,right,il,ir)
75
76  class Interval(object):
77      matcher = re.compile(r"([\[\(])(?!\()(.*?)\s*,\s*(.*?)([\]\)])")
78
79      def __init__(self,left,right,incl,incr):
80          assert right >= left
81          self.left = left
82          self.right = right
83          self.incl = incl
84          self.incr = incr
85
86      def __str__(self):
87          return ("[" if self.incl else "(") + \
88                 str(self.left)+" , "+str(self.right) + \
89                 ("]" if self.incr else ")")
90
91      def __repr__(self):
92          return self.__str__()
93
94      def contains(self,num):
95          return (self.left < num < self.right) or \
96                 (self.left == num and self.incl) or \
97                 (self.right == num and self.incr)
98
99  class Intersection:
100     def __init__(self,one,two):
101         self.one = one
102         self.two = two
103
104     def contains(self,num):
105         return self.one.contains(num) and self.two.contains(num)
106
107     def __str__(self):
108         l = str(self.one) if isinstance(self.one,Interval) else ("(%s)" % str(self.one))
109         r = str(self.two) if isinstance(self.two,Interval) else ("(%s)" % str(self.two))
110         return "%s \\cap %s" % (l,r)
111
112     def __repr__(self):
113         return self.__str__()
114
115
116 class Union:
117     def __init__(self,one,two):
118         self.one = one
119         self.two = two
120
```

```
121     def contains(self,num):
122         return self.one.contains(num) or self.two.contains(num)
123
124     def __str__(self):
125         l = str(self.one) if isinstance(self.one,Interval) else ("(%s)" % str(self.one))
126         r = str(self.two) if isinstance(self.two,Interval) else ("(%s)" % str(self.two))
127         return "%s \\cup %s" % (l,r)
128
129     def __repr__(self):
130         return self.__str__()
131
132 def find_matching_paren(string,dir=1):
133     print string
134     match = ')' if dir == 1 else '('
135     this = '(' if dir == 1 else ')'
136     tally = 0
137     ix = 0
138     while ix < (len(string)):
139         m = re.match(Interval.matcher,string[ix:])
140         if m:
141             ix += m.end()
142             continue
143         if tally == 0 and string[ix] == match:
144             return ix
145         elif string[ix] == this:
146             tally -= 1
147         elif string[ix] == match:
148             tally += 1
149         ix += 1
150     return None
151
152 def get_interesting_points(thing):
153     if isinstance(thing,Interval):
154         return set([thing.left,thing.right,sys.maxint,-sys.maxint - 1,0])
155     else:
156         return get_interesting_points(thing.one).union(get_interesting_points(thing.two))
157
158 classmap = {'U':Union,'N':Intersection}
159
160 def parse_single(string):
161     m = re.match(Interval.matcher,string)
162     if m is not None:
163         return str_to_range(string),string[m.end():]
164     elif string.startswith("("):
165         next = find_matching_paren(string[1:])
166         return parse_helper(string[1:1+next])[0],string[2+next:]
167     else:
168         raise Exception(string)
169
170 def parse_helper(string):
171     res1,new1 = parse_single(string)
172     if new1 == "":
173         return res1,""
174     op = new1[0]
175     res2,new2 = parse_single(new1[1:])
176     return classmap[op](res1,res2),new2
177
178
179 def parse(string):
180     return parse_helper(string)[0]
```

A.2 Detective

A.2.1 errors.py

```
1  # ERRORS.PY
2  # Simple interpretation of error messages
3  # hartz 2012
4
5  # This file is a part of CAT-SOOP Detective
6  # CAT-SOOP Detective is copyright (C) 2012 Adam Hartz.
7  #
8  # This program is free software: you can redistribute it and/or modify
9  # it under the terms of the GNU General Public License as published by
10 # the Free Software Foundation, either version 3 of the License, or
11 # (at your option) any later version.
12 #
13 # This program is distributed in the hope that it will be useful,
14 # but WITHOUT ANY WARRANTY; without even the implied warranty of
15 # MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE.  See the
16 # GNU General Public License for more details.
17 #
18 # You should have received a copy of the GNU General Public License
19 # along with this program.  If not, see <http://www.gnu.org/licenses/>.
20
21 import re
22 import ast
23 from trees import downward_search
24
25 ## BEGIN Pitfall Analysis
26 def node_specific_search(astnode,test_func):
27     if isinstance(astnode,ast.If) or isinstance(astnode,ast.While):
28         return downward_search(astnode.test,test_func) is not None
29     if isinstance(astnode,ast.Assign):
30         return downward_search(astnode.value,test_func) is not None
31     if isinstance(astnode,ast.Print):
32         n = [downward_search(i,test_func) for i in astnode.values]
33         return len([i for i in n if i is not None]) > 0
34     if isinstance(astnode,ast.Return):
35         return astnode.value is not None and downward_search(astnode.value,test_func) is not None
36
37 def pitfalls(astnode,code_lines,fname):
38     """
39     Explanation of Python programming pitfalls.  Future versions will consider more pitfalls.
40     """
41     # ^ vs **
42     if node_specific_search(astnode, lambda n: isinstance(n,ast.BinOp) and isinstance(n.op,ast.BitXor)):
43         out = "This line contains a caret (<tt>^</tt>), which is the syntax for a bitwise XOR operation."
44         out += " If you want exponentiation, use two asterisks (<tt>**</tt>) instead."
45         return out
46     # overwriting or hiding built-in variable
47     if isinstance(astnode,ast.Assign) and (isinstance(astnode.targets[0],ast.Name) and astnode.targets[0].id in
         __builtins__):
48         name = astnode.targets[0].id
49         if fname == '<module>':
50             #in the global scope...overwritten
51             out = "This line contains an assignment to a variable named <tt><b>%s</b></tt>.  " % name
52             out += "However, <tt><b>%s</b></tt> is also the name of an object built in to Python.  " % name
53             out += "This line will overwrite the built-in object so it can no longer be accessed."
54         else:
```

```
55              #inside of a function, so just hidden
56              out = "This line contains an assignment to a variable named <tt><b>%s</b></tt>.  " % name
57              out += "However, <tt><b>%s</b></tt> is also the name of an object built in to Python.  " % name
58              out += "This assignment will ''hide'' the built-in object, so that it will not be accessible"
59              out += " from within this function."
60          return out
61  ## END Pitfall Analysis
62
63  ## BEGIN Run-time Error Analysis
64  def explain(error_message,locals,globals):
65      for i in d:
66          l = list(d[i][0].finditer(error_message))
67          if len(l) == 0:
68              continue
69          m = l[0]
70          return {'msg':"A Python error occurred:<p>" +
71                  "<tt>%s</tt>" % ":".join(error_message.split(":")[1:]) +
72                  "<p>" + d[i][1](m,locals,globals)}
73
74
75  #functions to generate interpretations of specific error messages.
76
77  def namenotdefined_message(match,locals,globals):
78      varname = match.groups()[0]
79      msg = "This message means that the program is trying to access a variable called <b><tt>%s</tt></b>. "  %
            varname
80      msg += "However, there is no such variable in the current scope.  If this is the correct "
81      msg += " variable name, make sure it has been initialized first."
82      current_scope = {}
83      current_scope.update(globals)
84      if len(locals) > 0:
85          current_scope.update(locals)
86      current_scope.update(__builtins__) #we want to look at built-in names as well.
87      dist = sorted([(edit_distance(i,varname),i) for i in current_scope])
88      close = [j[1] for j in dist if j[0] <= 2]
89      if len(close) > 1:
90          msg += "  If not, did you mean to use one of the following variables? "
91          msg += "<p> %s" % "<br />\n".join(["<tt>%s</tt>" % i for i in close])
92      elif len(close) == 1:
93          msg += "  If not, did you mean to use the name <tt>%s</tt>?" % close[0]
94      else:
95          #if no variable names are close enough, pick those that are closest.
96          #this will probably do a solid job for long-enough variable names
97          nearest = [j[1] for j in dist if j[0] == min([k[0] for j in dist])]
98          if len(nearest) > 1:
99              msg += "  If not, did you mean to use one of the following variables? "
100             msg += "<p> %s" % "<br />\n".join(["<tt>%s</tt>" % i for i in nearest])
101         else:
102             msg += "  If not, did you mean to use the name <tt>%s</tt>?" % nearest[0]
103     return msg
104
105 def invalidoperation_message(match,locals,globals):
106     op,type1,type2 = match.groups()
107     if type1 == type2:
108         plural_thing = ("two <tt>%s</tt>s" % type1)
109     else:
110         plural_thing = "%s and %s" % (indefinite_article(type1),indefinite_article(type2))
111
112     msg = "This message means that the program is trying to combine "
113     msg += "two objects using an operator, but doesn't know how to do so."
114     msg += "<p>Specifically, this line is trying to combine %s using the <tt>%s</tt> operator, which " % (
```

```
            plural_thing,op)
115     msg += "is not supported."
116     return msg
117
118 def notsubscriptable_message(match,locals,globals):
119     typ = match.groups()[0]
120     msg = "Grabbing a single element from a collection using square brackets (<tt>[]</tt>)"
121     msg += " is referred to as <i>subscripting</i>.  This message means that the program is trying to subscript "
122     msg += "something that can't be subscripted (%s)" % indefinite_article(typ)
123
124     if typ == 'function':
125         msg += "<p>If you intended to call this function, you should use parentheses"
126         msg += " instead of square brackets."
127     return msg
128
129 def notcallable_message(match,locals,globals):
130     typ = match.groups()[0]
131     msg = "Executing the code stored within a function using round brackets (parentheses)"
132     msg += " is referred to as <i>calling</i> that function.  This message means that the program is trying to
            call "
133     msg += "something that can't be called (%s)" % indefinite_article(typ)
134
135     if typ in ('list','tuple','dict'):
136         msg += "<p>If you intended to index into this %s, you should use" % typ
137         msg += " square brackets (<tt>[]</tt>) instead of parentheses."
138     return msg
139
140 def notiterable_message(match,locals,globals):
141     typ = match.groups()[0]
142     msg = "Looping over the elements within a collection"
143     msg += " is referred to as <i>iterating over</i> that collection.  This message means that the "
144     msg += "program is trying to iterate over something "
145     msg += "something that can't be iterated over (%s)" % indefinite_article(typ)
146     return msg
147
148 # UTILITY METHODS USED ABOVE
149
150 def indefinite_article(string):
151     """
152     Prepend an appropriate indefinite article to the start of a string.
153     """
154     article = "an" if string.strip().lower()[0] in ('a','e','i','o','u') else "a"
155     return "%s <tt>%s</tt>" % (article, string.strip())
156
157 def edit_distance(seq1, seq2):
158     """
159     Find the Damerau-Levenshtein distance between two strings.
160
161     This code is written by Michael Homer, discovered at
162     http://mwh.geek.nz/2009/04/26/python-damerau-levenshtein-distance/
163     """
164     oneago = None
165     thisrow = range(1, len(seq2) + 1) + [0]
166     for x in xrange(len(seq1)):
167         twoago, oneago, thisrow = oneago, thisrow, [0] * len(seq2) + [x + 1]
168         for y in xrange(len(seq2)):
169             delcost = oneago[y] + 1
170             addcost = thisrow[y - 1] + 1
171             subcost = oneago[y - 1] + (seq1[x] != seq2[y])
172             thisrow[y] = min(delcost, addcost, subcost)
173             # This block deals with transpositions
```

```
            if (x > 0 and y > 0 and seq1[x] == seq2[y - 1]
                and seq1[x-1] == seq2[y] and seq1[x] != seq2[y]):
                thisrow[y] = min(thisrow[y], twoago[y - 2] + 1)
    return thisrow[len(seq2) - 1]


d = {
        'namenotdefined': (re.compile(r"NameError:(?: global)? name '(.*?)' is not defined"),
                           namenotdefined_message),

        'zerodivision': (re.compile(r"ZeroDivisionError: (.*)"),
                         lambda m,l,g: "This message means that the program is trying to divide by zero, which
                              would yield an undefined result.  Look carefully for places in this vicinity where
                              you are using division (<tt>/</tt>) or modulo (<tt>%</tt>); the second argument to
                              these operators cannot be zero."),

        'invalidoperation': (re.compile(r"TypeError: unsupported operand type\(s\) for (.*?): '(.*?)' and '(.*?)'
             "),
                             invalidoperation_message),

        'notsubscriptable': (re.compile(r"TypeError: '(.*?)' object is not subscriptable"),
                             notsubscriptable_message),

        'notcallable': (re.compile(r"TypeError: '(.*?)' object is not callable"),
                             notcallable_message),

        'indexoutofrange': (re.compile(r"list index out of range"),
                            lambda m,l,g: "This message means that the program is trying to grab the element at
                                 index <i>n</i> in a sequence, but there is no such item.  Remember that valid
                                 indices range from <tt>0</tt> to <tt>len(s)-1</tt> (or from <tt>-1</tt> to <tt>-
                                 len(s)</tt>) inclusive, where <tt>s</tt> is the sequence in question.")
        }
## END Run-time Error Analysis
```

A.2.2 explainer.py

```
1  # EXPLAINER.PY
2  # Simple explanation of lines of Python code
3  # hartz 2012
4
5  # This file is a part of CAT-SOOP Detective
6  # CAT-SOOP Detective is copyright (C) 2012 Adam Hartz.
7  #
8  # This program is free software: you can redistribute it and/or modify
9  # it under the terms of the GNU General Public License as published by
10 # the Free Software Foundation, either version 3 of the License, or
11 # (at your option) any later version.
12 #
13 # This program is distributed in the hope that it will be useful,
14 # but WITHOUT ANY WARRANTY; without even the implied warranty of
15 # MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE.  See the
16 # GNU General Public License for more details.
17 #
18 # You should have received a copy of the GNU General Public License
19 # along with this program.  If not, see <http://www.gnu.org/licenses/>.
20
21 from resolution import resolve
22 from trees import HTMLVisitor
23 import json
24 import ast
25 import traceback
26
27 def explain(node,locals,globals,fcache=None,event_type='',fname=''):
28     fcache = {} if fcache is None else fcache
29     a = HTMLVisitor()
30     out = {}
31
32     if event_type == 'return' and fname != "<module>":
33         out['msg'] = "The function <tt><b>%s</b></tt> is about to return." % fname
34
35     elif isinstance(node,ast.Assign):
36         #only support single assignment for now
37         i = node.targets[0]
38         out['msg'] = "This is an <i>assignment</i> statement.  Python will evaluate the expression"
39         out['msg'] += " on the right-hand side of the equals sign, and will "
40         if isinstance(i,ast.Name):
41             out['msg'] += "store the resulting value in variable %s." % HTMLVisitor().visit(i)
42         elif isinstance(i,ast.Subscript):
43             d = HTMLVisitor().visit(i.value)
44             x = HTMLVisitor().visit(i.slice.value) # assume slice is a single Index
45             out['msg'] += "attempt to store the resulting value in variable %s at index %s" % (d,x)
46         else:
47             out['msg'] += "attempt to store the resulting value."
48
49         try:
50             r = resolve(node.value,locals,globals,fcache)
51             out['res'] = [((a.visit(x) if x != 'ERROR' else "<font color='red'><tt>ERROR!</tt></font>"),y) for (x
                   ,y) in r]
52         except:
53             out['res'] = None
54
55         if out['res'] is not None:
56             out['msg'] += "<p>The expression in question resolves as follows:"
57
58
```

```
59      elif isinstance(node, ast.FunctionDef):
60          i = node.name
61          if event_type != 'call':
62              out['msg'] = "This is a <i>function definition</i> statement.  Python will store this function "
63              out['msg'] += "in variable <b><tt>%s</tt></b> so that it may be called later." % i
64          else:
65              out['msg'] = "The function <b><tt>%s</tt></b>, which was defined earlier, is now being called." % i
66              out['msg'] += " Execution will now jump to line %d" % node.body[0].lineno
67
68      elif isinstance(node, ast.Return):
69          v = node.value
70          if v is not None:
71              out['msg'] = "This is a <i>return</i> statement.  Python will evaluate the given expression, and "
72              out['msg'] += "yield that value as the result of this function call."
73              try:
74                  r = resolve(node.value,locals,globals,fcache)
75                  out['res'] = [((a.visit(x) if x != 'ERROR' else "<font color='red'><tt>ERROR!</tt></font>"),y)
                        for (x,y) in r]
76              except:
77                  out['res'] = None
78              if out['res'] is not None:
79                  out['msg'] += "<p>The expression in question resolves as follows:"
80          else:
81              out['msg'] = "This is a <i>return</i> statement.  Since no expression was given, Python will "
82              out['msg'] += "yield <tt>None</tt> as the result of this function call."
83              out['res'] = None
84
85      elif isinstance(node,ast.Delete):
86          i = node.name
87          out['msg'] = "This is a <i>deletion</i> statement."
88
89      elif isinstance(node,ast.Print):
90          out['msg'] = "This is a <i>print</i> statement."
91          v = node.values
92          if len(v) == 0:
93              out['msg'] += "  Since no value was given, to be printed this will display a blank line."
94          if len(v) == 1:
95              out['msg'] += "  Python will evaluate the given expression, and display it to the console."
96              try:
97                  r = resolve(v[0],locals,globals,fcache)
98                  out['res'] = [((a.visit(x) if x != 'ERROR' else "<font color='red'><tt>ERROR!</tt></font>"),y)
                        for (x,y) in r]
99              except:
100                 out['res'] = None
101             if out['res'] is not None:
102                 out['msg'] += "<p>The expression in question resolves as follows:"
103         else:
104             out['msg'] += "  Python will evaluate the given expressions, and display them to the console,
                 separated by a space."
105             try:
106                 r = resolve(v,locals,globals,fcache)
107                 out['res'] = [((a.visit(x) if x != 'ERROR' else "<font color='red'><tt>ERROR!</tt></font>"),y)
                        for (x,y) in r]
108             except:
109                 out['res'] = None
110             if out['res'] is not None:
111                 out['msg'] += "<p>The values in question resolve as follows:"
112
113
114     elif isinstance(node,ast.If):
115         t = node.body[0].lineno
```

```
116             try:
117                 f = node.orelse[0].lineno
118             except:
119                 f = None
120             out['msg'] = "This is an <i>if</i> statement.  Python will evaluate the given expression."
121             out['msg'] += "  If it evaluates to <tt>True</tt>, Python will jump to line %d.  "  % t
122             if f is not None:
123                 out['msg'] += "If it evaluates to <tt>False</tt>, Python will jump instead to line %d." % f
124 
125             try:
126                 r = resolve(node.test,locals,globals,fcache)
127                 out['res'] = [((a.visit(x) if x != 'ERROR' else "<font color='red'><tt>ERROR!</tt></font>"),y) for (x
                        ,y) in r]
128             except:
129                 out['res'] = None
130             if out['res'] is not None:
131                 out['msg'] += "<p>The expression in question resolves as follows:"
132 
133         elif isinstance(node,ast.For):
134             iterable = HTMLVisitor().visit(node.iter)
135             target = HTMLVisitor().visit(node.target)
136             out['msg'] = "This is a <i>for</i> loop.  Python will run the given code block once for each element in "
137             out['msg'] += "<tt><b>%s</b></tt>, each time setting a variable <tt><b>%s</b></tt> equal to the next
                    element in <tt><b>%s</b></tt>." % (iterable,target,iterable)
138 
139         elif isinstance(node,ast.While):
140             t = node.body[0].lineno
141             out['msg'] = "This is a <i>while</i> loop.  Python will evaluate the given expression."
142             out['msg'] += "  If it evaluates to <tt>True</tt>, Python will jump to line %d, execute the "  % t
143             out['msg'] += " code in that block, and return here to check again."
144             out['msg'] += " If it instead evaluates to <tt>False</tt>, Python will skip this code block altogether."
145 
146             try:
147                 r = resolve(node.test,locals,globals,fcache)
148                 out['res'] = [((a.visit(x) if x != 'ERROR' else "<font color='red'><tt>ERROR!</tt></font>"),y) for (x
                        ,y) in r]
149             except:
150                 out['res'] = None
151             if out['res'] is not None:
152                 out['msg'] += "<p>The expression in question resolves as follows:"
153 
154         elif isinstance(node,ast.Break):
155             out['msg'] = "This is a <i>break</i> statement. If it is given inside of a loop, this statement will
                    cause Python to jump outside the loop, skipping the rest of the code block for this iteration and
                    all subsequent iterations. If given outside of a loop, this statement will cause an error."
156 
157         elif isinstance(node,ast.Continue):
158             out['msg'] = "This is a <i>continue</i> statement. If it is given inside of a loop, this statement will
                    cause Python to jump to the top of the loop, skipping the rest of the code block for this iteration.
                      If given outside of a loop, this statement will cause an error."
159 
160         elif isinstance(node,ast.Pass):
161             out['msg'] = "This is a <i>pass</i> statement, which tells Python to do nothing."
162 
163 
164         else:
165             out['msg'] = ''
166 
167         return out
```

A.2.3 hz_encoder.py

```
1  # HZ_ENCODER.PY
2  # encode/decode output from hz_logger, etc
3  # hartz 2012
4
5  # !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
6  # Most of the code in this file is taken directly from pg_encoder:
7  # Online Python Tutor
8  # Copyright (C) 2010-2011 Philip J. Guo (philip@pgbovine.net)
9  # https://github.com/pgbovine/OnlinePythonTutor/
10 # !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
11
12 # This file is a part of CAT-SOOP Detective
13 # CAT-SOOP Detective is copyright (C) 2012 Adam Hartz.
14 #
15 # This program is free software: you can redistribute it and/or modify
16 # it under the terms of the GNU General Public License as published by
17 # the Free Software Foundation, either version 3 of the License, or
18 # (at your option) any later version.
19 #
20 # This program is distributed in the hope that it will be useful,
21 # but WITHOUT ANY WARRANTY; without even the implied warranty of
22 # MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE.  See the
23 # GNU General Public License for more details.
24 #
25 # You should have received a copy of the GNU General Public License
26 # along with this program.  If not, see <http://www.gnu.org/licenses/>.
27
28
29 # Given an arbitrary piece of Python data, encode it in such a manner
30 # that it can be later encoded into JSON.
31 #   http://json.org/
32 #
33 # We use this function to encode run-time traces of data structures
34 # to send to the front-end.
35 #
36 # Format:
37 #   * None, int, long, float, str, bool - unchanged
38 #     (json.dumps encodes these fine verbatim)
39 #   * list      - ['LIST', unique_id, elt1, elt2, elt3, ..., eltN]
40 #   * tuple     - ['TUPLE', unique_id, elt1, elt2, elt3, ..., eltN]
41 #   * set       - ['SET', unique_id, elt1, elt2, elt3, ..., eltN]
42 #   * dict      - ['DICT', unique_id, [key1, value1], [key2, value2], ..., [keyN, valueN]]
43 #   * instance - ['INSTANCE', class name, unique_id, [attr1, value1], [attr2, value2], ..., [attrN, valueN]]
44 #   * class     - ['CLASS', class name, unique_id, [list of superclass names], [attr1, value1], [attr2, value2],
       ..., [attrN, valueN]]
45 #   * circular reference - ['CIRCULAR_REF', unique_id]
46 #   * other     - [<type name>, unique_id, string representation of object]
47 #
48 # the unique_id is derived from id(), which allows us to explicitly
49 # capture aliasing of compound values
50
51 # Key: real ID from id()
52 # Value: a small integer for greater readability, set by cur_small_id
53 real_to_small_IDs = {}
54 cur_small_id = 1
55
56 import re, types,ast
57 typeRE = re.compile("<type '(.*)'>")
58 classRE = re.compile("<class '(.*)'>")
```

```
59
60  def encode(dat, ignore_id=False):
61    def encode_helper(dat, compound_obj_ids):
62      # primitive type
63      if dat is None or \
64         type(dat) in (int, long, float, str, bool):
65        return dat
66      # compound type
67      else:
68        my_id = id(dat)
69
70        global cur_small_id
71        if my_id not in real_to_small_IDs:
72          if ignore_id:
73            real_to_small_IDs[my_id] = 99999
74          else:
75            real_to_small_IDs[my_id] = cur_small_id
76          cur_small_id += 1
77
78        if my_id in compound_obj_ids:
79          return ['CIRCULAR_REF', real_to_small_IDs[my_id]]
80
81        new_compound_obj_ids = compound_obj_ids.union([my_id])
82
83        typ = type(dat)
84
85        my_small_id = real_to_small_IDs[my_id]
86
87        if typ == list:
88          ret = ['LIST', my_small_id]
89          for e in dat: ret.append(encode_helper(e, new_compound_obj_ids))
90        elif typ == tuple:
91          ret = ['TUPLE', my_small_id]
92          for e in dat: ret.append(encode_helper(e, new_compound_obj_ids))
93        elif typ == set:
94          ret = ['SET', my_small_id]
95          for e in dat: ret.append(encode_helper(e, new_compound_obj_ids))
96        elif typ == dict:
97          ret = ['DICT', my_small_id]
98          for (k,v) in dat.iteritems():
99            # don't display some built-in locals ...
100           if k not in ('__module__', '__return__'):
101             ret.append([encode_helper(k, new_compound_obj_ids), encode_helper(v, new_compound_obj_ids)])
102       elif typ in (types.InstanceType, types.ClassType, types.TypeType) or \
103            classRE.match(str(typ)):
104         # ugh, classRE match is a bit of a hack :(
105         if typ == types.InstanceType or classRE.match(str(typ)):
106           ret = ['INSTANCE', dat.__class__.__name__, my_small_id]
107         else:
108           superclass_names = [e.__name__ for e in dat.__bases__]
109           ret = ['CLASS', dat.__name__, my_small_id, superclass_names]
110
111         # traverse inside of its __dict__ to grab attributes
112         # (filter out useless-seeming ones):
113         user_attrs = sorted([e for e in dat.__dict__.keys()
114                              if e not in ('__doc__', '__module__', '__return__')])
115
116         for attr in user_attrs:
117           ret.append([encode_helper(attr, new_compound_obj_ids), encode_helper(dat.__dict__[attr],
                 new_compound_obj_ids)])
118       else:
```

```
119             typeStr = str(typ)
120             m = typeRE.match(typeStr)
121             assert m, typ
122             ret = [m.group(1), my_small_id, str(dat)]
123 
124         return ret
125 
126     return encode_helper(dat, set())
127 
128 
129 #hartz 2012
130 def decode(encoded): #will not work for user-defined classes, but we're okay with that for now...
131     out = None
132     if type(encoded) != list:
133         out = encoded #encoded is just a python literal
134     else:
135         typ = encoded[0]
136         if typ=='LIST':
137             out = [decode(i) for i in encoded[2:]]
138         elif typ=='TUPLE':
139             out = tuple(decode(i) for i in encoded[2:])
140         elif typ=='SET':
141             out = set([decode(i) for i in encoded[2:]])
142         elif typ=='DICT':
143             out = dict([(decode(k),decode(v)) for (k,v) in encoded[2:]])
144         elif typ=='complex':
145             out = eval(encoded[-1])
146     return out
147 
148 #hartz 2012
149 def encode_ast(p):
150     if type(p) in (int,long,float,complex):
151         out = ast.Num()
152         out.n = p
153     elif type(p) == str:
154         out = ast.Str()
155         out.s = p
156     elif type(p) == list:
157         out = ast.List()
158         out.elts = [encode_ast(i) for i in p]
159     elif type(p) == tuple:
160         out = ast.Tuple()
161         out.elts = [encode_ast(i) for i in p]
162     elif type(p) == dict:
163         out = ast.Dict()
164         keys = p.keys()
165         values = [p[k] for k in keys]
166         out.keys = [encode_ast(i) for i in keys]
167         out.values = [encode_ast(i) for i in values]
168     elif type(p) == set:
169         out = ast.Call()
170         out.func = ast.Name()
171         out.func.id = 'set'
172         out.args = [encode_ast(list(p))]
173     elif type(p) == bool:
174         out = ast.Name()
175         out.id = str(p)
176     else:
177         return None
178     out.ctx = ast.Load()
179     return out
```

A.2.4 hz_logger.py

```
# HZLOGGER.PY
# trace an execution of a Python script
# hartz 2012

# !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
# Most of the code in this file is taken directly from pg_logger:
# Online Python Tutor
# Copyright (C) 2010-2011 Philip J. Guo (philip@pgbovine.net)
# https://github.com/pgbovine/OnlinePythonTutor/
# !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

# This file is a part of CAT-SOOP Detective
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#
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#
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# along with this program.  If not, see <http://www.gnu.org/licenses/>.

import sys
import bdb # the KEY import here!
import os
import re
import traceback

import cStringIO
import trees
import hz_encoder
import errors
import resolution
import explainer
import ast
import pickle

# upper-bound on the number of executed lines, in order to guard against
# infinite loops
MAX_EXECUTED_LINES = 200

def set_max_executed_lines(m):
  global MAX_EXECUTED_LINES
  MAX_EXECUTED_LINES = m

IGNORE_VARS = set(('__stdout__', '__builtins__', '__name__', '__exception__'))

def get_user_stdout(frame):
  return frame.f_globals['__stdout__'].getvalue()

def get_user_globals(frame):
  d = filter_var_dict(frame.f_globals)
  # also filter out __return__ for globals only, but NOT for locals
  if '__return__' in d:
```

```
60      del d['__return__']
61    return d
62
63  def get_user_locals(frame):
64    return filter_var_dict(frame.f_locals)
65
66  def filter_var_dict(d):
67    ret = {}
68    for (k,v) in d.iteritems():
69      if k not in IGNORE_VARS:
70        ret[k] = v
71    return ret
72
73
74  class HZLogger(bdb.Bdb):
75
76      def __init__(self, finalizer_func, ignore_id=False):
77          bdb.Bdb.__init__(self)
78          self.mainpyfile = ''
79          self._wait_for_mainpyfile = 0
80
81          # a function that takes the output trace as a parameter and
82          # processes it
83          self.finalizer_func = finalizer_func
84
85          # each entry contains a dict with the information for a single
86          # executed line
87          self.trace = []
88
89          # don't print out a custom ID for each object
90          # (for regression testing)
91          self.ignore_id = ignore_id
92
93
94      def reset(self):
95          bdb.Bdb.reset(self)
96          self.forget()
97
98      def forget(self):
99          self.lineno = None
100         self.stack = []
101         self.curindex = 0
102         self.curframe = None
103
104     def setup(self, f, t):
105         self.forget()
106         self.stack, self.curindex = self.get_stack(f, t)
107         self.curframe = self.stack[self.curindex][0]
108
109
110     # Override Bdb methods
111
112     def user_call(self, frame, argument_list):
113         """This method is called when there is the remote possibility
114         that we ever need to stop in this function."""
115         if self._wait_for_mainpyfile:
116             return
117         if self.stop_here(frame):
118             self.interaction(frame, None, 'call')
119
120     def user_line(self, frame):
```

```
121         """This function is called when we stop or break at this line."""
122         if self._wait_for_mainpyfile:
123             if (self.canonic(frame.f_code.co_filename) != "<string>" or
124                 frame.f_lineno <= 0):
125                 return
126             self._wait_for_mainpyfile = 0
127         self.interaction(frame, None, 'step_line')
128 
129     def user_return(self, frame, return_value):
130         """This function is called when a return trap is set here."""
131         frame.f_locals['__return__'] = return_value
132         self.interaction(frame, None, 'return')
133 
134     def user_exception(self, frame, exc_info):
135         exc_type, exc_value, exc_traceback = exc_info
136         """This function is called if an exception occurs,
137         but only if we are to stop at or just below this level."""
138         frame.f_locals['__exception__'] = exc_type, exc_value
139         if type(exc_type) == type(''):
140             exc_type_name = exc_type
141         else: exc_type_name = exc_type.__name__
142         self.interaction(frame, exc_traceback, 'exception')
143 
144 
145     # General interaction function
146 
147     def interaction(self, frame, traceback, event_type):
148         self.setup(frame, traceback)
149         tos = self.stack[self.curindex]
150         lineno = tos[1]
151 
152         # each element is a pair of (function name, ENCODED locals dict)
153         encoded_stack_locals = []
154 
155         encoded_locals = None
156         encoded_globals = None
157 
158         # climb up until you find '<module>', which is (hopefully) the global scope
159         i = self.curindex
160         while True:
161           cur_frame = self.stack[i][0]
162           cur_name = cur_frame.f_code.co_name
163           if cur_name == '<module>':
164             break
165 
166           # special case for lambdas - grab their line numbers too
167           if cur_name == '<lambda>':
168             cur_name = 'lambda on line ' + str(cur_frame.f_code.co_firstlineno)
169           elif cur_name == '':
170             cur_name = 'unnamed function'
171 
172           # encode in a JSON-friendly format now, in order to prevent ill
173           # effects of aliasing later down the line ...
174           encoded_locals = {}
175           for (k, v) in get_user_locals(cur_frame).iteritems():
176             # don't display some built-in locals ...
177             if k != '__module__':
178               encoded_locals[k] = hz_encoder.encode(v, self.ignore_id)
179 
180           encoded_stack_locals.append((cur_name, encoded_locals))
181           i -= 1
```

```
182
183         # encode in a JSON-friendly format now, in order to prevent ill
184         # effects of aliasing later down the line ...
185         encoded_globals = {}
186         for (k, v) in get_user_globals(tos[0]).iteritems():
187           encoded_globals[k] = hz_encoder.encode(v, self.ignore_id)
188
189
190         #this seems a little convoluted, but i think i like it better than just making a copy
191         #hartz 2012
192         real_locals = dict([(k,hz_encoder.decode(v)) for (k,v) in (encoded_locals or {}).iteritems()])
193         real_globals = dict([(k,hz_encoder.decode(v)) for (k,v) in (encoded_globals or {}).iteritems()])
194         cur_node = trees.downward_search(self.tree,lambda n: n.lineno == lineno)
195
196         trace_entry = dict(line=lineno,
197                            event=event_type,
198                            func_name=tos[0].f_code.co_name,
199                            globals=encoded_globals,
200                            stack_locals=encoded_stack_locals,
201                            stdout=get_user_stdout(tos[0]))
202
203         # if there's an exception, then record its info:
204         if event_type == 'exception':
205           # always check in f_locals
206           exc = frame.f_locals['__exception__']
207           trace_entry['exception_msg'] = exc[0].__name__ + ': ' + str(exc[1])
208           trace_entry['explanation'] = errors.explain(trace_entry['exception_msg'],real_locals,real_globals) #hz
209         else:
210           trace_entry['explanation'] = explainer.explain(cur_node,real_locals,real_globals,event_type=event_type,
                fname=trace_entry['func_name']) #hz
211
212         # hz 2012
213         try:
214           trace_entry['warnings'] = errors.pitfalls(cur_node,self.script_str,trace_entry['func_name'])
215         except:
216           trace_entry['warnings'] = None
217         # /hz 2012
218
219         self.trace.append(trace_entry)
220
221         if len(self.trace) >= MAX_EXECUTED_LINES:
222           self.trace.append(dict(event='instruction_limit_reached', exception_msg='(stopped after ' + str(
                MAX_EXECUTED_LINES) + ' steps to prevent possible infinite loop)'))
223           self.force_terminate()
224
225         self.forget()
226
227     def _runscript(self, script_str):
228         # When bdb sets tracing, a number of call and line events happens
229         # BEFORE debugger even reaches user's code (and the exact sequence of
230         # events depends on python version). So we take special measures to
231         # avoid stopping before we reach the main script (see user_line and
232         # user_call for details).
233         self._wait_for_mainpyfile = 1
234
235         script_str = script_str.replace("\r","")
236
237         # ok, let's try to sorta 'sandbox' the user script by not
238         # allowing certain potentially dangerous operations:
239         user_builtins = {}
240         for (k,v) in __builtins__.iteritems():
```

```
241           if k in ('reload', 'input', 'apply', 'open', 'compile',
242                    'file', 'eval', 'execfile', '__import__',
243                    'exit', 'quit', 'raw_input',
244                    'dir', 'globals', 'locals', 'vars',
245                    'compile'):
246             continue
247           user_builtins[k] = v
248
249         # redirect stdout of the user program to a memory buffer
250         user_stdout = cStringIO.StringIO()
251         sys.stdout = user_stdout
252
253         user_globals = {"__name__"    : "__main__",
254                         "__builtins__" : user_builtins,
255                         "__stdout__" : user_stdout}
256
257         # BEGIN hartz 2012
258         # store this as an instance variable so we can inspect it later...
259         self.script_str = script_str.splitlines()
260
261         # parse the input script down into an AST; we'll use this later when
262         # generating explanations, etc.
263         self.tree = ast.parse(script_str)
264
265         # END hartz 2012
266
267         try:
268           self.run(script_str, user_globals, user_globals)
269         # sys.exit ...
270         except SystemExit:
271           sys.exit(0)
272         except:
273           traceback.print_exc() # uncomment this to see the REAL exception msg
274
275           trace_entry = dict(event='uncaught_exception')
276
277           exc = sys.exc_info()[1]
278           if hasattr(exc, 'lineno'):
279             trace_entry['line'] = exc.lineno
280           if hasattr(exc, 'offset'):
281             trace_entry['offset'] = exc.offset
282
283           if hasattr(exc, 'msg') or hasattr(exc, 'message'): # hartz 2012 ('message' would be nice, too)
284             try:
285                 m = exc.msg
286             except:
287                 m = exc.message
288             trace_entry['exception_msg'] = "Error: " + (m)
289           else:
290             trace_entry['exception_msg'] = "Unknown error"
291
292           self.trace.append(trace_entry)
293           self.finalize()
294           sys.exit(0) # need to forceably STOP execution
295
296       def force_terminate(self):
297         self.finalize()
298         sys.exit(0) # need to forceably STOP execution
299
300
301       def finalize(self):
```

```
302         sys.stdout = sys.__stdout__
303         assert len(self.trace) <= (MAX_EXECUTED_LINES + 1)
304
305         # filter all entries after 'return' from '<module>', since they
306         # seem extraneous:
307         res = []
308         for e in self.trace:
309           res.append(e)
310           if e['event'] == 'return' and e['func_name'] == '<module>':
311             break
312
313         # another hack: if the SECOND to last entry is an 'exception'
314         # and the last entry is return from <module>, then axe the last
315         # entry, for aesthetic reasons :)
316         if len(res) >= 2 and \
317            res[-2]['event'] == 'exception' and \
318            res[-1]['event'] == 'return' and res[-1]['func_name'] == '<module>':
319           res.pop()
320
321         self.trace = res
322
323         #for e in self.trace: print e
324
325         self.finalizer_func(self.trace)
326
327
328   # the MAIN meaty function!!!
329   def exec_script_str(script_str, finalizer_func, ignore_id=False):
330     logger = HZLogger(finalizer_func, ignore_id)
331     logger._runscript(script_str)
332     logger.finalize()
333
334
335   def exec_file_and_pretty_print(mainpyfile):
336     import pprint
337
338     if not os.path.exists(mainpyfile):
339       print 'Error:', mainpyfile, 'does not exist'
340       sys.exit(1)
341
342     def pretty_print(output_lst):
343       for e in output_lst:
344         pprint.pprint(e)
345
346     output_lst = exec_script_str(open(mainpyfile).read(), pretty_print)
347
348
349   if __name__ == '__main__':
350     # need this round-about import to get __builtins__ to work :0
351     import hz_logger
352     hz_logger.exec_file_and_pretty_print(sys.argv[1])
```

A.2.5 resolution.py

```
1  # RESOLUTION.PY
2  # (pseudo-) instruction-level resolution of Python programs
3  # hartz 2012
4
5  # This file is a part of CAT-SOOP Detective
6  # CAT-SOOP Detective is copyright (C) 2012 Adam Hartz.
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13 # This program is distributed in the hope that it will be useful,
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16 # GNU General Public License for more details.
17 #
18 # You should have received a copy of the GNU General Public License
19 # along with this program.  If not, see <http://www.gnu.org/licenses/>.
20
21
22 import ast
23 import traceback
24 from hz_encoder import decode,encode_ast
25 import sys
26
27 def set_lineno(tree,recursive=True):
28     tree.lineno = 1
29     tree.col_offset = 1
30     if recursive:
31         for i in ast.iter_child_nodes(tree):
32             set_lineno(i)
33
34 def evaluate_tree(tree,locals,globals):
35     """
36     Given an AST node and a set of variables, return the value to which
37     the given node would resolve in the specified environment.
38     """
39
40     set_lineno(tree,recursive=True)
41     e = ast.Expression(tree)
42     code = compile(e,"<submitted code>","eval")
43     out = eval(code,globals,locals)
44     return out
45
46 #AST Class -> English mapping
47 operators = {ast.Add:'Addition', ast.Sub:'Subtraction', ast.Mult:'Multiplication', ast.Div:'Division',
48              ast.Mod:'Modulo', ast.Pow:'Exponentiation', ast.LShift:'Left-shift',
49              ast.RShift:'Right-shift', ast.BitOr:'Bit-wise OR', ast.BitXor:'Bit-wise XOR',
50              ast.BitAnd:'Bit-wise AND',ast.FloorDiv:'Floor (integer) division'}
51
52 unary_operators = {ast.Invert:"Bit-wise Inversion", ast.Not:"Logical NOT",
53                    ast.USub:"Unary Subtraction (Negation)", ast.UAdd:"Unary Addition (Identity)"}
54
55 comp_operators = {ast.Eq:"'Equal' Comparison", ast.NotEq:"'Not-equal' Comparison",
56                   ast.Lt:"'Less-than' Comparison", ast.LtE:"'Less-than-or-equal-to' Comparison",
57                   ast.Gt:"'Greater-than' Comparison", ast.GtE:"'Greater-than-or-equal-to' Comparison",
58                   ast.Is:"'Is' Comparison (Object Identity)",
59                   ast.IsNot:"'Is-not' Comparison (Object Identity)",
```

```
60                  ast.In:"'In' Comparison", ast.NotIn:"'Not-in' Comparison"}
61
62  DEBUG = True
63
64  def resolve(node,locals,globals,function_cache=None): #assume globals,locals have been decoded by here...
65      """
66      Return a list of tuples (state,action), where state is the current state (an AST Node)
67      is the state of the resolution, and action (a string) is a description of the action
68      taken to reach that state from the previous one.
69      """
70      if function_cache is None:
71          function_cache = {}
72
73      out = None
74
75      if isinstance(node,ast.Num) or isinstance(node,ast.Str):
76          out = [(node,None)]
77
78      elif isinstance(node,ast.Name):
79          i = node.id
80          msg = "Loading variable <tt><b>%s</b></tt>" % i
81          try:
82              internal = evaluate_tree(node,locals,globals) #might throw exception, be ready to catch.
83          except:
84              return [(node,None),('ERROR',msg)]
85          out = [(node,None),(encode_ast(internal),msg)]
86
87      elif isinstance(node,ast.List):
88          out = [(node,None)]
89          #resolve each element in turn
90          for ix in xrange(len(node.elts)):
91              if out[-1][0] == 'ERROR':
92                  break
93              res = resolve(node.elts[ix],locals,globals)
94              last = out[-1][0].elts
95              front = last[:ix]
96              back = last[ix+1:]
97              for i in res[1:]:
98                  a,msg = i
99                  if a == 'ERROR':
100                     out.append(i)
101                     break
102                 l = ast.List()
103                 l.ctx = ast.Load()
104                 l.elts = front + [a] + back
105                 out.append((l,msg))
106
107     elif isinstance(node,ast.Tuple):
108         #as with lists, resolve each element in turn
109         out = [(node,None)]
110         for ix in xrange(len(node.elts)):
111             if out[-1][0] == 'ERROR':
112                 break
113             res = resolve(node.elts[ix],locals,globals)
114             last = out[-1][0].elts
115             front = last[:ix]
116             back = last[ix+1:]
117             for i in res[1:]:
118                 a,msg = i
119                 if a == 'ERROR':
120                     out.append(i)
```

```
121                     break
122                 l = ast.Tuple()
123                 l.ctx = ast.Load()
124                 l.elts = front + [a] + back
125                 out.append((l,msg))
126
127     elif isinstance(node,ast.Dict):
128         # really tedious, but...resolve each key->val pair
129         out = [(node,None)]
130         for ix in xrange(len(node.keys)):
131             if out[-1][0] == 'ERROR':
132                 break
133             last = out[-1][0]
134             front_keys = last.keys[:ix]
135             back_keys = last.keys[ix+1:]
136             front_vals = last.values[:ix]
137             back_vals = last.values[ix+1:]
138             #resolve the key step-by-step
139             reskey = resolve(node.keys[ix], locals, globals)
140             resval = resolve(node.values[ix], locals, globals)
141             for jx in xrange(1,len(reskey)):
142                 a,msg = reskey[jx]
143                 if a == 'ERROR':
144                     out.append(reskey[jx])
145                     break
146                 d = ast.Dict()
147                 d.ctx = ast.Load()
148                 d.keys = front_keys+[a]+back_keys
149                 d.values = last.values[:]
150                 out.append((d,msg))
151             #once we've resolved the key, resolve the associated value
152             last = out[-1][0]
153             if out[-1][0] == 'ERROR':
154                 break
155             for i in resval[1:]:
156                 a,msg = i
157                 if a == 'ERROR':
158                     out.append(i)
159                     break
160                 d = ast.Dict()
161                 d.ctx = ast.Load()
162                 d.keys = last.keys[:]
163                 d.values = front_vals + [a] + back_vals
164                 out.append((d,msg))
165
166     elif isinstance(node,ast.BinOp):
167         # resolve left side of tree
168         out = [(node,None)]
169         for i in resolve(node.left,locals,globals)[1:]:
170             if i[0] == 'ERROR':
171                 out.append(i)
172                 break
173             new = ast.BinOp()
174             new.op = out[-1][0].op
175             new.ctx = ast.Load()
176             new.left = i[0]
177             new.right = out[-1][0].right
178             out.append((new,i[1]))
179         if out[-1][0] == 'ERROR':
180             return out
181         #resolve right side of tree
```

```
182         for i in resolve(node.right,locals,globals)[1:]:
183             if i[0] == 'ERROR':
184                 out.append(i)
185                 break
186             new = ast.BinOp()
187             new.op = out[-1][0].op
188             new.ctx = ast.Load()
189             new.left = out[-1][0].left
190             new.right = i[0]
191             out.append((new,i[1]))
192         #if we've made it this far, resolve the operation itself
193         msg = operators[out[0][0].op.__class__]
194         try:
195             pythonic = evaluate_tree(out[-1][0],{},{})
196         except:
197             out.append(('ERROR',msg))
198             return out
199         out.append((encode_ast(pythonic),msg))
200 
201     elif isinstance(node,ast.BoolOp):
202         out = [(node,None)]
203         #Need to be careful here...
204 
205         #first consider the AND operator
206         if isinstance(node.op,ast.And):
207             for ix in xrange(len(node.values)):
208                 #resolve each value in turn
209                 if out[-1][0] == 'ERROR':
210                     break
211                 res = resolve(node.values[ix],locals,globals)
212                 last = out[-1][0].values
213                 front = last[:ix]
214                 back = last[ix+1:]
215                 for i in res[1:]:
216                     a,msg = i
217                     if a == 'ERROR':
218                         out.append(i)
219                         break
220                     l = ast.BoolOp()
221                     l.op = out[0][0].op
222                     l.ctx = ast.Load()
223                     l.values = front + [a] + back
224                     out.append((l,msg))
225                 pythonic = evaluate_tree(a,{},{})
226                 bval = bool(pythonic)
227                 #if one of the fully-resolved values isn't a boolean,
228                 #cast it to one for clarity
229                 if not isinstance(pythonic,bool):
230                     new = bool(pythonic)
231                     a = encode_ast(new)
232                     l = ast.BoolOp()
233                     l.op = out[0][0].op
234                     l.ctx = ast.Load()
235                     l.values = front + [a] + back
236                     out.append((l,"Casting to <tt>bool</tt> type"))
237                 #if we hit a False, the whole BoolOp is going to resolve to False,
238                 #WITHOUT CHECKING THE OTHER VALUES
239                 if bval == False:
240                     break
241             if not bval:
242                 out.append((encode_ast(False),"'And' operator"))
```

```
243             else:
244                 out.append((encode_ast(True),"'And' operator"))
245 
246         #OR is exactly analogous
247         elif isinstance(node.op,ast.Or):
248             for ix in xrange(len(node.values)):
249                 #resolve each value in turn
250                 if out[-1][0] == 'ERROR':
251                     break
252                 res = resolve(node.values[ix],locals,globals)
253                 last = out[-1][0].values
254                 front = last[:ix]
255                 back = last[ix+1:]
256                 for i in res[1:]:
257                     a,msg = i
258                     if a == 'ERROR':
259                         out.append(i)
260                         break
261                     l = ast.BoolOp()
262                     l.op = out[0][0].op
263                     l.ctx = ast.Load()
264                     l.values = front + [a] + back
265                     out.append((l,msg))
266                 pythonic = evaluate_tree(a,{},{})
267                 bval = bool(pythonic)
268                 #if one of the fully-resolved values isn't a boolean,
269                 #cast it to one for clarity
270                 if not isinstance(pythonic,bool):
271                     new = bool(pythonic)
272                     a = encode_ast(new)
273                     l = ast.BoolOp()
274                     l.op = out[0][0].op
275                     l.ctx = ast.Load()
276                     l.values = front + [a] + back
277                     out.append((l,"Casting to <tt>bool</tt> type"))
278                 #if we hit a True, the whole BoolOp is going to resolve to True,
279                 #WITHOUT CHECKING THE OTHER VALUES
280                 if bval == True:
281                     break
282             if not bval:
283                 out.append((encode_ast(False),"'Or' operator"))
284             else:
285                 out.append((encode_ast(True),"'Or' operator"))
286 
287     elif isinstance(node,ast.Compare):
288         out = [(node,None)]
289         for i in resolve(node.left,locals,globals)[1:]:
290             if i[0] == 'ERROR':
291                 out.append(i)
292                 break
293             new = ast.Compare()
294             new.ops = out[-1][0].ops
295             new.ctx = ast.Load()
296             new.left = i[0]
297             new.comparators = out[-1][0].comparators
298             out.append((new,i[1]))
299         if out[-1][0] == 'ERROR':
300             return out
301         for ix in xrange(len(out[-1][0].comparators)):
302             if out[-1][0] == 'ERROR':
303                 break
```

```
304             front = out[-1][0].comparators[:ix]
305             back = out[-1][0].comparators[ix+1:]
306             for i in resolve(node.comparators[ix],locals,globals)[1:]:
307                 if i[0] == 'ERROR':
308                     out.append(i)
309                     break
310                 new = ast.Compare()
311                 new.ops = out[-1][0].ops
312                 new.ctx = ast.Load()
313                 new.left = out[-1][0].left
314                 new.comparators = front + [i[0]] + back
315                 out.append((new,i[1]))
316         msg = comp_operators[out[0][0].ops[0].__class__] if len(out[0][0].ops) == 1 else "Multiple Comparisons"
317         try:
318             pythonic = evaluate_tree(out[-1][0],{},{})
319         except:
320             out.append(('ERROR',msg))
321             return out
322         out.append((encode_ast(pythonic),msg))
323 
324     elif isinstance(node,ast.UnaryOp):
325         out = [(node,None)]
326         for i in resolve(node.operand,locals,globals)[1:]:
327             if i[0] == 'ERROR':
328                 out.append(i)
329                 break
330             new = ast.UnaryOp()
331             new.op = out[-1][0].op
332             new.ctx = ast.Load()
333             new.operand = i[0]
334             out.append((new,i[1]))
335         msg = unary_operators[out[0][0].op.__class__]
336         try:
337             pythonic = evaluate_tree(out[-1][0],{},{})
338         except:
339             out.append(('ERROR',msg))
340             return out
341         out.append((encode_ast(pythonic),msg))
342 
343     elif isinstance(node,ast.Subscript): #subscript, but assume only single Index
344         out = [(node,None)]
345         #not sure how best to deal with this.  show whole collection?  for now i'll
346         #avoid that.
347         for i in resolve(node.slice.value,locals,globals)[1:]:
348             if i[0] == 'ERROR':
349                 out.append(i)
350                 break
351             new = ast.Subscript()
352             new.ctx = ast.Load()
353             new.value = out[0][0].value
354             new.slice = ast.Index()
355             new.slice.ctx = ast.Load()
356             new.slice.value = i[0]
357             out.append((new,i[1]))
358         try:
359             pythonic = evaluate_tree(out[-1][0],locals,globals) #need vars here!
360         except:
361             out.append(('ERROR',msg))
362             return out
363         msg = 'Subscripting'
364         out.append((encode_ast(pythonic),msg))
```

```
365
366         return out
```

A.2.6 trees.py

```
1  # TREES.PY
2  # utilities for dealing with trees
3  # hartz 2012
4
5  # This file is a part of CAT-SOOP Detective
6  # CAT-SOOP Detective is copyright (C) 2012 Adam Hartz.
7  #
8  # This program is free software: you can redistribute it and/or modify
9  # it under the terms of the GNU General Public License as published by
10 # the Free Software Foundation, either version 3 of the License, or
11 # (at your option) any later version.
12 #
13 # This program is distributed in the hope that it will be useful,
14 # but WITHOUT ANY WARRANTY; without even the implied warranty of
15 # MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE.  See the
16 # GNU General Public License for more details.
17 #
18 # You should have received a copy of the GNU General Public License
19 # along with this program.  If not, see <http://www.gnu.org/licenses/>.
20
21 import ast
22
23 def downward_search(tree,test_func):
24     """
25     Search down an AST for a node n such that test_func(n) is True.
26     Return that node, or None if no such node exists in the tree.
27     """
28     try:
29         if test_func(tree):
30             return tree
31     except:
32         pass
33     for child in ast.iter_child_nodes(tree):
34         n = downward_search(child,test_func)
35         if n:
36             return n
37     return None
38
39 class HTMLVisitor(ast.NodeVisitor):
40     """
41     Visitor which walks an AST and returns an HTML Representation of it.
42
43     Borrowed structure from Geoff Reedy (http://stackoverflow.com/users/166955/geoff-reedy)
44     Found at http://stackoverflow.com/questions/3867028/converting-a-python-numeric-expression-to-latex
45
46     Precedence based on 5.15 at http://docs.python.org/reference/expressions.html
47     """
48
49     def prec(self, n):
50         return getattr(self, 'prec_'+n.__class__.__name__, getattr(self, 'generic_prec'))(n)
51
52     #Prepare yourself for an obnoxious enumeration of Classes...
53
54     def visit_Call(self, n):
55         func = self.visit(n.func)
56         args = ', '.join(map(self.visit, n.args))
57         return r'%s<tt>(</tt>%s<tt>)</tt>' % (func, args)
58
59     def prec_Call(self, n):
```

```
60          return 1000
61
62      def visit_Name(self, n):
63          return "<tt><b>%s</b></tt>" % n.id if n.id not in ('True','False') else "<tt>%s</tt>" % n.id
64
65      def prec_Name(self, n):
66          return 1000
67
68      def visit_UnaryOp(self, n):
69          if self.prec(n.op) > self.prec(n.operand):
70              return r'%s <tt>(</tt>%s<tt>)</tt>' % (self.visit(n.op), self.visit(n.operand))
71          else:
72              return r'%s %s' % (self.visit(n.op), self.visit(n.operand))
73
74      def prec_UnaryOp(self, n):
75          return self.prec(n.op)
76
77      def visit_BinOp(self, n):
78          if self.prec(n.op) >= self.prec(n.left):
79              left = r'<tt>(</tt>%s<tt>)</tt>' % self.visit(n.left)
80          else:
81              left = self.visit(n.left)
82          if self.prec(n.op) >= self.prec(n.right):
83              right = r'<tt>(</tt>%s<tt>)</tt>' % self.visit(n.right)
84          else:
85              right = self.visit(n.right)
86          if isinstance(n.op, ast.Div):
87              return r'%s <tt>/</tt> %s' % (left, right)
88          elif isinstance(n.op, ast.FloorDiv):
89              return r'%s <tt>//</tt> %s' % (left, right)
90          elif isinstance(n.op, ast.Pow):
91              return r'%s<tt>**</tt>%s' % (left, right)
92          else:
93              return r'%s %s %s' % (left, self.visit(n.op), right)
94
95      def visit_BoolOp(self,n):
96          opstr = self.visit(n.op)
97          vals = []
98          for i in n.values:
99              if self.prec(i) < self.prec(n.op):
100                 thingy = r'<tt>(</tt>%s<tt>)</tt>' % self.visit(i)
101             else:
102                 thingy = self.visit(i)
103             vals.append(thingy)
104         return (' '+opstr+' ').join(vals)
105
106     def prec_BinOp(self, n):
107         return self.prec(n.op)
108
109     def visit_Sub(self, n):
110         return '<tt>-</tt>'
111
112     def prec_Sub(self, n):
113         return 8
114
115     def visit_Add(self, n):
116         return '<tt>+</tt>'
117
118     def prec_Add(self, n):
119         return 8
120
```

```
121     def visit_Mult(self, n):
122         return '<tt>*</tt>'
123
124     def prec_Mult(self, n):
125         return 9
126
127     def visit_Mod(self, n):
128         return '<tt>%%</tt>'
129
130     def prec_Mod(self, n):
131         return 9
132
133     def prec_Pow(self, n):
134         return 11
135
136     def prec_Div(self, n):
137         return 9
138
139     def prec_FloorDiv(self, n):
140         return 9
141
142     def visit_LShift(self, n):
143         return '<tt>%lt;%lt;</tt>'
144
145     def prec_LShift(self,n):
146         return 7
147
148     def visit_RShift(self, n):
149         return '<tt>&gt;&gt;</tt>'
150
151     def prec_RShift(self,n):
152         return 7
153
154     def visit_BitOr(self, n):
155         return '<tt>|</tt>'
156
157     def prec_BitOr(self,n):
158         return 5
159
160     def visit_BitXor(self, n):
161         return '<tt>^</tt>'
162
163     def prec_BitXor(self,n):
164         return 6
165
166     def visit_BitAnd(self, n):
167         return '<tt>&</tt>'
168
169     def prec_BitAnd(self,n):
170         return 6.5
171
172     def visit_Invert(self, n):
173         return '<tt>~</tt>'
174
175     def prec_Invert(self, n):
176         return 10
177
178     def visit_And(self, n):
179         return '<tt>and</tt>'
180
181     def prec_And(self, n):
```

```
182             return 2
183
184         def visit_Or(self, n):
185             return '<tt>or</tt>'
186
187         def prec_Or(self, n):
188             return 1
189
190         def visit_Not(self, n):
191             return '<tt>not</tt>'
192
193         def prec_Not(self, n):
194             return 3
195
196         def visit_UAdd(self, n):
197             return ''
198
199         def prec_UAdd(self, n):
200             return 10
201
202         def visit_USub(self, n):
203             return '<tt>-</tt>'
204
205         def prec_USub(self, n):
206             return 10
207
208         def visit_Num(self, n):
209             return "<tt>%s</tt>" % str(n.n)
210
211         def prec_Num(self, n):
212             return 1000
213
214         def visit_List(self,l):
215             return '<tt>[</tt>' + "<tt>, </tt>".join([self.visit(i) for i in l.elts])  +  '<tt>]</tt>'
216
217         def prec_List(self,l):
218             return 1000
219
220         def visit_Tuple(self,l):
221             if len(l.elts) == 0:
222                 return "tuple()"
223             return '<tt>(</tt>' + "<tt>, </tt>".join([self.visit(i) for i in l.elts]) + "<tt>, </tt>" if len(l.elts)
                    > 1 else ""  +  '<tt>)</tt>'
224
225         def prec_Tuple(self,l):
226             return 1000
227
228         def visit_Dict(self,d):
229             return '<tt>{</tt>' + "<tt>, </tt>".join(["%s<tt>: </tt>%s" % (self.visit(k),self.visit(v)) for (k,v) in
                    zip(d.keys,d.values)]) + '<tt>}</tt>'
230
231         def prec_Dict(self,l):
232             return 1000
233
234         def visit_Compare(self,c):
235             return self.visit(c.left) + " " + " ".join(["%s %s" % (self.visit(a),self.visit(b)) for (a,b) in zip(c.
                    ops,c.comparators)])
236
237         def prec_Compare(self,n):
238             return 4
239
```

```
240     prec_Lt = prec_LtE = prec_Gt = prec_GtE = prec_Eq = prec_NotEq = prec_Is = prec_IsNot = prec_In = prec_NotIn
            = prec_Compare
241
242     def visit_Lt(self,n):
243         return "<tt>&lt;</tt>"
244
245     def visit_LtE(self,n):
246         return "<tt>&lt;=</tt>"
247
248     def visit_Gt(self,n):
249         return "<tt>&gt;</tt>"
250
251     def visit_GtE(self,n):
252         return "<tt>&gt;=</tt>"
253
254     def visit_Eq(self,n):
255         return "<tt>==</tt>"
256
257     def visit_NotEq(self,n):
258         return "<tt>!=</tt>"
259
260     def visit_Is(self,n):
261         return "<tt>is</tt>"
262
263     def visit_IsNot(self,n):
264         return "<tt>is not</tt>"
265
266     def visit_In(self,n):
267         return "<tt>in</tt>"
268
269     def visit_NotIn(self,n):
270         return "<tt>not in</tt>"
271
272     def visit_Str(self,s):
273         return "<tt>%s</tt>" % repr(s.s)
274
275     def visit_Subscript(self,s):
276         return "%s<tt>[</tt>%s<tt>]</tt>" % (self.visit(s.value),self.visit(s.slice.value))
277
278     def prec_Subscript(self,n):
279         return 1000
280
281     def prec_Str(self,n):
282         return 1000
283
284     def generic_visit(self, n):
285         if isinstance(n, ast.AST):
286             return r'%s<tt>(</tt>%s<tt>)</tt>' % (n.__class__.__name__, '<tt>, </tt>'.join(map(self.visit, [
                    getattr(n, f) for f in n._fields])))
287         else:
288             return str(n)
289
290     def generic_prec(self, n):
291         return 0
```

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