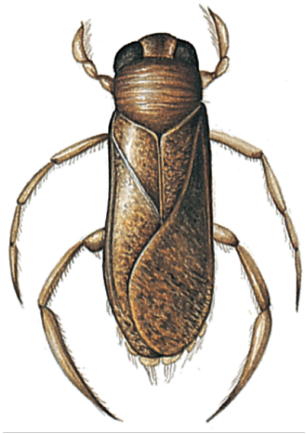
CS 1
Introduction to Computer Programming

Lecture 17: November 16, 2012

How to think about debugging



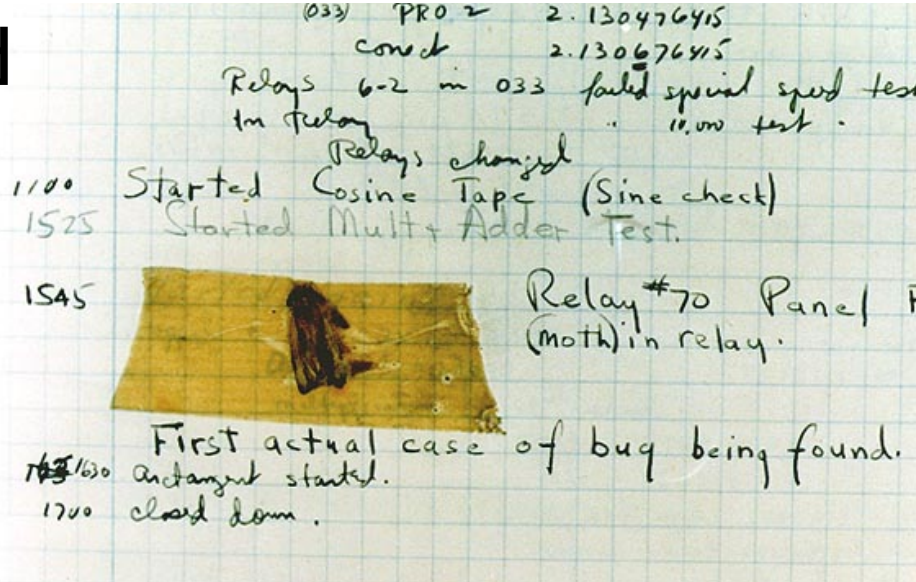
Program Failures

- So, you wrote your program.
- And, guess what? It doesn't work. ☹

- Your program has a **bug** in it
- Somehow, you must track down the bug and fix it
- Need to **debug** the program

Program Failures (2)

- True origin of the term "bug" is unclear, but computers have failed because of actual bugs!
- 1947: Harvard Mark II relay-based computer stopped working
- A *moth* was found wedged between a relay's contacts!



Bugs = Defects + Failures

- Helpful to break down concept of a "bug" into two more fundamental components:
- Program contains a defect in the code, due to a design or implementation issue
- This defect is manifested as a failure of some kind
  - Program reports an error when you run it, or it produces an incorrect result, it crashes, etc.

Bugs = Defects + Failures (2)

- Several different kinds of errors
- Syntax errors: didn't use language correctly
  - The Python interpreter simply doesn't understand what you tried to say
  - e.g. you forgot a closing-quote on a string constant
- Semantic or logical errors: the interpreter understands your code, but implementation is still incorrect in some way
  - e.g. you tried to add that string to a number

Finding Bugs

- The majority of the work in fixing a bug is usually finding the defect that produces it
- Usually, once you identify the defective code, the proper fix becomes obvious
- If the overall *design* is defective, this can be much more difficult
  - Can require redesigning and reimplementing a large portion of the program

Example: Defective Design

- Math Department Candy Store:
  - First candy costs ten cents
  - Each subsequent candy costs ten cents more than the previous candy
  - You have one dollar to spend

- How many candies can you buy?
  - (Four!)

Example: Defective Design (2)

- Let's write a Python program to do this:

```
price = 0.10   # First candy is 10 cents
budget = 1.00  # I have one dollar
count = 0      # Start with no candies
while budget >= price:
    count += 1         # Buy another candy!
    budget -= price
    price += 0.10      # Price goes up

print 'I bought %d candies.' % count
print 'I have $%f left.' % budget
```

- How many candies can you buy?

Example: Defective Design (3)

- This program produces the wrong result!

```
I bought 3 candies.
I have $0.400000 left.
```

- Problem: floating-point numbers are an approximation
  - In fact, cannot exactly represent numbers like 0.1 in floating-point!
- Using floats to represent monetary amounts is a defective design
  - Can use integers to represent all monetary values in cents, or use other decimal representations

Finding Bugs (2)

- The defect is only the *cause* of the failure, but it is not the failure itself!
  - The defect will immediately begin to affect the program's state…
  - …but the effects may not become visible for some time
- The greater the separation between defect and failure, the harder it is to diagnose the defect from the failure

Finding Bugs (3)

- If the defect directly causes the failure:
  - Simply need to identify the location where the program fails. Can usually fix bug very quickly.
- Normally the defect and failure are separated from each other
  - Often in different functions
  - Sometimes separated by a significant amount of execution time (hours, days, weeks!)
- How to determine actual cause of failure?

Simple Examples

- Code:

```
def f1(a, b):
    return 'a' + b

f1(3, 4)
```

Defect and failure are on the same line.

- Error:

```
Traceback (most recent call last):
  File "<stdin>", line 1, in <module>
  File "<stdin>", line 2, in f1
TypeError: cannot concatenate 'str'
 and 'int' objects
```

Simple Examples (2)

- Code:

```
def f1(a, b):
    return a + b
def f2(a):
    return f1('a', 10)
f2(6)
```

Failure occurs here…

Defect is here!

- Error:

```
Traceback (most recent call last):
  File "<stdin>", line 1, in <module>
  File "<stdin>", line 2, in f2
  File "<stdin>", line 2, in f1
TypeError: cannot concatenate 'str' and
  'int' objects
```

Simple Examples (3)

- Traceback tells you where to start looking

```
Traceback (most recent call last):
  File "<stdin>", line 1, in <module>
  File "<stdin>", line 2, in f2
  File "<stdin>", line 2, in f1
TypeError: cannot concatenate 'str' and
 'int' objects
```

  - Last line is where the failure occurred
- But the actual defect could be anywhere along the line
  - …could also be code executed any time before the failure occurred

Preemptive Bug Detection

- Want defects to manifest as failures quickly!
  - Don't want much time to pass, or else they will be harder to find
- One common technique for causing defects to manifest quickly is using assertions
- Frequently have conditions that you expect to be true at certain points in your program
  - Explicitly state these in an assertion, in your code
  - At runtime, the assertion is checked: if it's false, the program is stopped immediately!

Example: Mastermind Functions

- Have to write two functions for Mastermind:
  - `count_exact_matches(code, guess)`
  - `count_letter_matches(code, guess)`
- Expectations for the inputs?
  - Both `code` and `guess` are strings of length 4
- Expectations for the outputs?
  - Result will always be between 0 and 4
- These can be enforced as assertions
  - If they are violated as our program runs, we'll be notified immediately

Python Assertions

- Python provides an **`assert`** statement
- Form 1: **`assert cond`**
  - Tests ***`cond`*** ; if it's false then an **`AssertionError`** exception is raised
- Form 2: **`assert cond, mesg`**
  - Similar to Form 1, but ***`mesg`*** is included in the **`AssertionError`** if it fails

Python Assertions (2)

- Example:

```
Line 1: def count_exact_matches(code, guess):
Line 2:     assert len(code) == 4
Line 3:     assert len(guess) == 4
            ...  # rest of implementation

    >>> count_exact_matches('ABCD', 'ABCDE')
    Traceback (most recent call last):
      File "<stdin>", line 1, in <module>
      File "<stdin>", line 3, in
          count_exact_matches
    AssertionError
```

Tells us which assertion failed

Python Assertions (3)

- A bit difficult to figure out location, plus we don't know what we actually got passed!
- Update the assertion to include more detail:

```
def count_exact_matches(code, guess):
    assert len(code) == 4, \
        'Invalid code: %s' % code
    assert len(guess) == 4, \
        'Invalid guess: %s' % guess
    ...  # rest of implementation

>>> count_exact_matches('ABCD', 'ABCDE')
AssertionError: Invalid guess: ABCDE
```

Aside: Argument Types

- Python doesn't enforce constraints on the types of arguments, variables, etc.
- `count_exact_matches(code, guess)`
  - Can pass any valid Python type for code and guess!
  - Can't enforce the expected types in the function declaration
- But, there is a way to enforce argument types using assertions

Aside: Argument Types (2)

- Python provides a special **`types`** module:

```
from types import *
```

  - Module is designed to be imported this way
- Allows us to create assertions like this:

```
def count_exact_matches(code, guess):
    assert type(code) == StringType, \
      "code %s isn't a string!" % code
    assert len(code) == 4
    ... # etc.
```

  - **`type()`** built-in function returns type of arg

Aside: Argument Types (3)

- It's actually somewhat discouraged in Python to enforce types too strictly
  - Part of Python's strength is its flexibility
- However, if a function definitely requires its arguments to be specific types, this mechanism is very effective
  - The moment you misuse the function, you will be alerted with an error message!

Python Assertions (4)

- Definitely use assertions in your code!
  - Saves *so much* time when debugging!!!
- You should even be willing to perform large, slow tests in assertions
  - Doesn't matter how fast your program is, if it produces the wrong answers
- Assertions can be turned off once you are confident your program works properly
  - `python -O program.py`

Detective Work

- Once you have observed a failure in your program, you have a mystery to solve!
- One thing a good detective never does:
  - Guess randomly!
- The programming version of this:
  - Make random guesses about the cause, and try various changes
  - Called "the shotgun approach," and "monkeys on a typewriter"
  - (The results are just as good, too.)

Detective Work (2)

- Instead, must consider the clues, and track down the defect from details of the failure
- Identify the issue first. *Then* make the fix.
  - Hunt bugs with a rifle, not with a shotgun.
  - Not as likely to introduce other defects, too.
- A major problem with bug-fixing: causing **regressions**
  - In the process of fixing a bug, you actually introduce other new bugs! (*Very* depressing.)

Detective Work (3)

- Limiting the effects of code-changes is yet another reason to keep functions small!
  - (and to avoid using global variables!)
- Functions usually perform computations in isolation from each other
- Fixing a bug in a small function is *far* less likely to affect other parts of the program, than fixing a bug in a very large function

Step 1: Reproduce the Failure

- Before you can do anything else, you must find a way to reproduce the failure
  - Recreate the steps that caused the program to fail
  - Was it specific data inputs? Was it a specific interaction with the program?
- At this point in your programming career, may simply be to re-run your program
  - As your programs become more complex, reproducing failures becomes more involved

Step 1: Reproduce the Failure

- Reproducing the failure is very important, for three major reasons:
  1. **So you can watch it fail.** See exactly what the program was doing as it crashed and burned.
  2. **So you can zero in on the cause.** If the program fails in some circumstances but not in others, this will give you *hints* as to what part of the program actually contains the defect.
  3. **So you can test if you actually fixed it.** If you can reliably cause the failure, and your fix makes it go away, you win!

Step 1: Reproduce the Failure

- Reasons for reproducing the failure:
  1. **So you can watch it fail.** See exactly what the program was doing as it crashed and burned.
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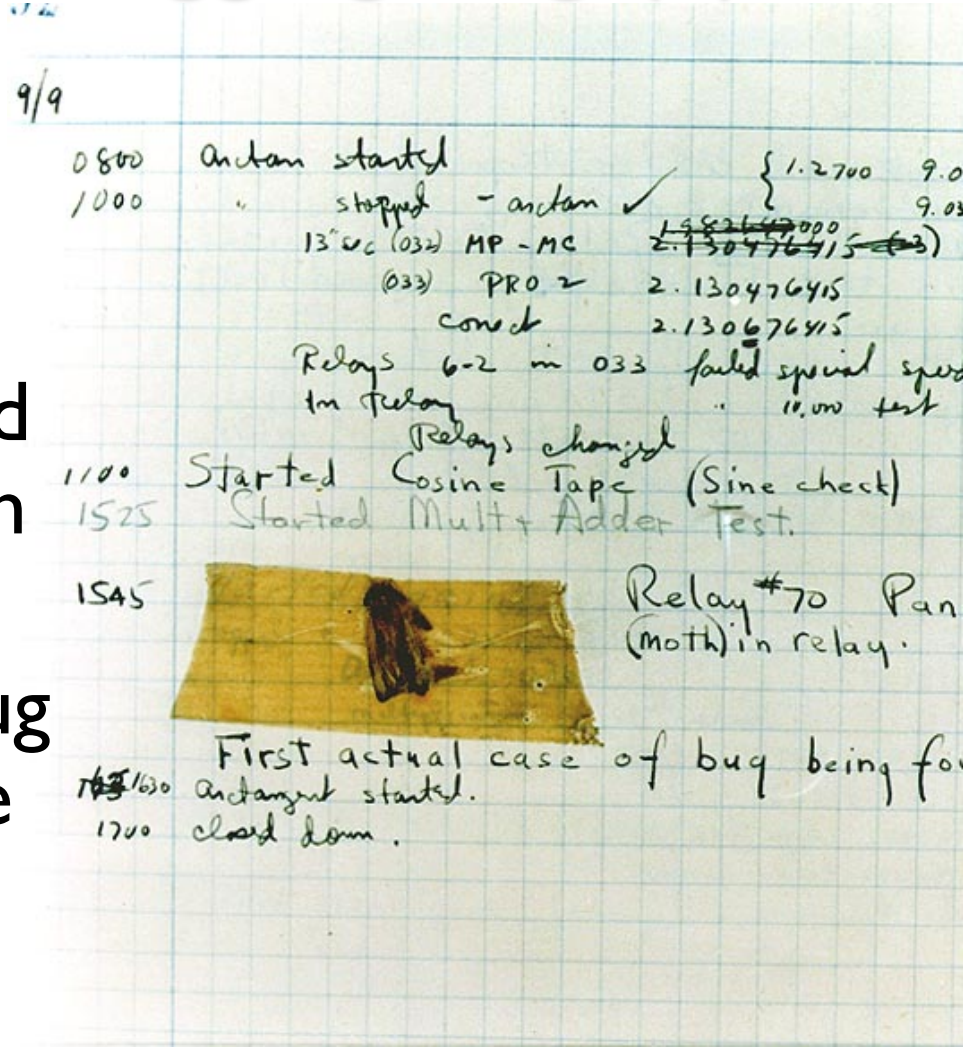
  3. **So you can test if you actually fixed it.** If you can reliably cause the failure, and your fix makes it go away, you win!
- None of these reasons require special tools
- *Debugging tools* can help with steps 1 and 2

Technique: Keep a Debugging Log!

- When debugging nasty issues, it's extremely helpful to keep a record of your efforts (hand-written or typed, it doesn't matter)
  - A general description of the failure
  - Inputs or circumstances when the failure occurs
  - Ideas of potential causes, along with the efforts you made to verify your ideas, and indications for or against each theory
- Extremely effective for helping focus your thoughts and ideas

Technique: Debugging Log (2)

- The "first" bug:
- This is part of a debugging log
- And it's displayed at Smithsonian in Washington DC
- Maybe *your* debug logs will become just as notable one day!



Technique: Debugging Log (3)

- A debugging log also allows you to set aside an issue, and pick it up later
- It's generally a very bad idea to debug while exhausted
  - Thought processes aren't clear. You can't reason effectively about the bug.
  - Tend to revert to "monkeys on a typewriter" mode
  - Put it down and walk away. Come back later when you're fresh.

Step 2: Isolate the Failure

- So your program fails. And you know how to make it fail.
- Problem: the defect is only in a small part of your code
  - Need to zero in on the part of the code that's actually flawed
- Goal: try to devise the smallest possible scenario that still causes the failure to occur
  - If the scenario is small, there won't be very much code involved
  - The less code that's involved, the easier it is to find the defect

Example: Failure Isolation

- A common programming task: process very large data files
  - e.g. data collected from an experiment
  - Example: the Large Hadron Collider (LHC) produces 700 megabytes of data *per second!*
- But, you have a bug:
  - Your program generally works, but…
  - One data file causes your program to crash.
  - And the data file is 2.1 gigabytes long.
  - What do you do?

Example: Failure Isolation (2)

- You have the offending file, so you can reproduce the failure
  - Still, a lot of code runs before the failure occurs
- Want to narrow in on the actual cause of the bug:
  - Cut the file down until you have the *minimal* portion that still causes the crash
  - Perhaps the program crashes because the file contains a few bad values
  - If you're lucky, might even identify a handful of input lines that causes the problem
  - Should make it much easier to identify and resolve the defect

Example: Failure Isolation (3)

- What if you can't get the issue to reproduce by trying smaller parts of the file in isolation?
- That would be a much harder bug to track down
  - But, would indicate that the bug is triggered by some characteristic of the file *as a whole*
  - e.g. maybe the file's size causes some memory issue
  - e.g. maybe a combination of values read from the file causes the failure
- Here is the point: You learn more about the nature of the defect by trying to isolate it
  - Record these things in your debugging log!

Step 2: Isolate the Failure (2)

- Previous example involved trying to isolate the *inputs* that cause the failure
- Can also try to isolate the *general area of your program's code* that contains the failure
- Example: Mastermind program
  - The program behaves oddly when you run it
  - You have found inputs that reproduce the behavior
  - Now, want to narrow down the specific area of your program's code with the failure

Step 2: Isolate the Failure (3)

- Python is *great* for isolating failures!
  - Can load your program into the interpreter, and then call various operations individually

    ```
    python -i stupid_broken_program.py
    ```

    (or just load into WingIDE!)
- Mastermind, continued
  - Load your program, then test the important functions individually:

    ```
    make_random_code()
    count_exact_matches(code, guess)
    count_letter_matches(code, guess)
    ```
  - Does each operation behave correctly?
  - If not, the code you need to review is very small!

Technique: Understand the System!

- Knowing where to start with bugs really requires you to understand the system being debugged. For example:
  - What are the major operations of the program?
  - What parts of the code perform each of these functions?
- If a failure manifests when a specific feature is used, you know what files or functions to start with.

Understand the System! (2)

- Are there parts of the code that are always executed?
  - If a failure manifests in a variety of scenarios, this would be a likely location for the defect.
- Are there parts of the code that can be disabled or removed, and test run again?
- If you disable part of the code, and the failure still occurs:
  - The defect is *not* in the code we disabled!

Understand the System! (3)

- Can ask similar questions when analyzing the *inputs* to your programs
- Are there parts of the code that only run on specific inputs, or sequences of inputs?
  - In other words, can you trigger specific paths through your program with certain inputs?
- If you can exercise every path through your code, bugs won't be able to hide

Example: Scoring a Blackjack Hand

- Given a blackjack hand-scoring function, how would we exercise all code paths?
  - Try the function with an empty hand
  - Try it with a hand containing no aces
  - Try it with a hand containing one ace that can be scored as 11 without busting
  - Try it with a hand containing one ace that must be scored as 1 to not bust
  - Try it with multiple aces, where some (but not all) aces must be scored as 1 to not bust
  - Try it with multiple aces, where all aces must be scored as 1 to not bust

Understand the System! (4)

- Whole point of understanding the system:
  - You are performing experiments with your program, making observations of its behavior
  - You need to *correlate* the observed behaviors with various parts of your program's code
  - The more effective you are at doing this, the faster you will zero in on the location of bugs
- Debugging involves a lot of thinking…

Understand the System! (5)

- Both positive *and negative* correlations are helpful!
- If you can say, "This behavior is definitely not caused by the code in this part of the program," that also helps narrow down the source of the issue.

Technique: Disabling Code

- How to disable a portion of the code depends on the specific language being used, as well as the program's structure
- In Python, can comment out code:

```
def foo():
    ''' This is my awesome function that
    doesn't work. '''
    bar()
    # FIXME:  this may be buggy...
    # abc('def')  # Do something amazing!
    return xyz()
```

Technique: Disabling Code (2)

- Can also wrap the code in triple-quotes

```
def foo():
    ''' This is my awesome function that
    doesn't work. '''
    ''' FIXME:  This may be buggy...
    bar()
    abc('def')  # Do something amazing!
    '''
    return xyz()
```

- (This won't work if the code you're wrapping also contains triple-quotes…)

Technique: Use Simple Test Cases

- If you can't chop down the input data, and you can't chop down the program itself:
- Can create very simple test cases to exercise simple paths through the code
- Have already seen this earlier:
  - Mastermind: test the individual operations for correctness
  - Blackjack scoring function: use a battery of tests to exhaustively exercise the code

Step 3: Identify the Defect Itself

- If you have completed the first two steps:
  - You probably have defect's location narrowed down to a relatively small part of your code
- Now, need to identify possible origins of the failure, and eliminate them one by one
  - Requires that you reproduce failure yet again, and watch what your program does as it fails
  - If you can't peer into the program's execution, you cannot identify the exact origin of the bug

Step 3: Identify the Defect Itself (2)

- Several different approaches for this step:
  - Add logging/printing/debugging output to your program
  - Or, run your program in a debugger to single-step through the failure scenario
- Both approaches have the same goal:
  - Examine the state-changes your program makes, correlated with the specific lines of code making those changes
  - Determine the exact point in time when your program begins to create invalid state

Step 3: Identify the Defect Itself (3)

- What is a "debugger" ?!
  - A separate tool that allows you to execute your code line by line, and to examine the program's state as it runs
  - (Sadly, it doesn't find the bugs for you, yet…)
- Using a debugger is a more powerful, less intrusive way of watching your code run
  - It is definitely possible to introduce other bugs while adding your debug output
- Really only essential for compiled languages
  - Python has a debugger, but often unnecessary

Technique: Printing Out Details

- A very common approach for debugging programs:
  - Add `print` statements to the code, then rerun your failure scenario
  - Then, pore through the debug output to see what happened

- If you're going to add debug output, might as well print out everything that might be relevant

Technique: Printing Out Details (2)

- Common scenario:
  - The program fails.
  - Programmer suspects a particular cause of the failure, and adds debug-output to the program to explore that specific cause.
  - Guess what? It's not that!
  - Programmer has to go back and print out more details…
- When adding debug output, print all details that could be useful to know!
  - Allows you to evaluate multiple potential causes in less time

Technique: Printing Out Details (3)

- Also, make sure each output line is unique

```
def foo(n):
    b = 0
    for i in range(n):
        print b
        b = bar(i, b)
        print b
        xyz(b)
```

- When you run this function, how do you tell what output is from what line?
- Want to make each line unique somehow:

```
print '1:  b = %d' % b
```

Step 4: Fix Defect, Verify Fix

- Once the actual defect is found, usually straightforward to fix
  - …unless it's a design issue. This is why it's always good to design up front.
- You aren't finished fixing the bug until you verify the fix
- By this point, you should have a way to reproduce the failure…
  - Retry your tests and see if the failure is gone
  - If no more failures, you're done!

Step 4: Fix Defect, Verify Fix (2)

- Bug fixes can introduce new defects into the code
  - Such defects are called *regressions*
- Usually occurs when:
  - The actual cause of the bug wasn't fully understood
  - Or, the impact of the bug-fix isn't fully understood
- Good programmers also check for regressions:
  - Verify that the original bug is fixed
  - Also perform other tests to ensure that no new bugs were introduced
- Be a good programmer ☺
  - It will save you tons of time and frustration!

Some Notes about Fixing Bugs

- **Believe your observations, not your suspicions.**
- A common scenario:
  - The program fails. The programmer *suspects* a particular issue, and focuses his attention there.
  - However, there is no indication that the suspected cause is the *actual* cause of problem.
  - Sometimes this will cause you to miss obvious details that clearly indicate the actual source of the problem.

Some Notes about Fixing Bugs (2)

- **If you didn't fix it, it isn't fixed!**
- Another common scenario:
  - An intermittent failure is occurring.
  - You made a few stabs at fixing it, but you still really don't know what causes the problem or how to reproduce it.
- You definitely can't correlate any of your "fixes" with the problem

Some Notes about Fixing Bugs (3)

- **If you didn't fix it, it isn't fixed!**
- It is very appealing to assume that if a bug hasn't occurred recently, it must be fixed.
  - You may even avoid focused testing on that issue (mainly because you really don't want to know…)
- Normally, these problems usually come back.
  - Usually during a demo, or when your code is being graded.

Next Time

- More on exception handling
  - Raising exceptions in one function and catching them in another function
  - The runtime stack