Testing

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The material for this lecture is drawn, in part, from
The Practice of Programming (Kernighan & Pike) Chapter 6

Bugs, Bugs Everywhere

"On two occasions I have been asked [by members of Parliament!], 'Pray, Mr. Babbage, if you put into the machine wrong figures, will the right answers come out?' I am not able rightly to apprehend the kind of confusion of ideas that could provoke such a question."
– Charles Babbage

"Program testing can be quite effective for showing the presence of bugs, but is hopelessly inadequate for showing their absence."
– Edsger Dijkstra

"Beware of bugs in the above code; I have only proved it correct, not tried it."
– Donald Knuth

Goals of this Lecture

- Help you learn about:
  - Internal testing
  - External testing
  - General testing strategies
- Why?
  - Hard to know if a large program works properly
  - When developing a large program, a power programmer expends ***at least*** **as much effort writing test code** as he/she expends writing the program itself
  - A power programmer is comfortable with a wide variety of program testing techniques and strategies

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Program Verification

- Ideally: Prove that your program is correct
  - Can you **prove** properties of the program?
  - Can you **prove** that it even terminates?!!!

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Program Testing

- Pragmatically: Convince yourself that your program probably works

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External vs. Internal Testing

- Types of testing
  - External testing
    - Designing data to test your program
  - Internal testing
    - Designing your program to test itself

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External Testing

- External testing: Designing data to test your program
- External testing taxonomy
  (1) Boundary testing
  (2) Statement testing
  (3) Path testing
  (4) Stress testing
- Let's consider one at a time…

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Boundary Testing

(1) Boundary testing

- "A testing technique using input values at, just below, and just above, the defined limits of an input domain; and with input values causing outputs to be at, just below, and just above, the defined limits of an output domain."
  – Glossary of Computerized System and Software Development Terminology
- Alias corner case testing
- Almost all bugs occur at boundary conditions
- If program works for boundary conditions, it probably works for all others

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Boundary Testing Example

- Code to get line from stdin and put in character array

```
int i;
char s[MAXLINE];
for (i=0; (s[i]=getchar()) != '\n' && i < MAXLINE-1; i++)
    ;
s[i] = '\0';
printf("String: |%s|\n", s);
```

- Boundary conditions
  - Input starts with '\n' (empty line)
    - Prints empty string (“\0”), so output is “||”
  - End of file before '\n‘
    - Keeps calling getchar() and storing ÿ in s[i]
  - End of file immediately (empty file)
    - Keeps calling getchar() and storing ÿ in s[i]

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Boundary Testing Example (cont.)

- Code to get line from stdin and put in character array

```
int i;
char s[MAXLINE];
for (i=0; (s[i]=getchar()) != '\n' && i < MAXLINE-1; i++)
    ;
s[i] = '\0';
printf("String: |%s|\n", s);
```

- Boundary conditions
  - Line exactly MAXLINE-1 characters long
    - Output is correct, with ‘\0’ in s[MAXLINE-1]
  - Line exactly MAXLINE characters long
    - Last character on the line is overwritten, and newline never read
  - Line more than MAXLINE characters long
    - Some characters, plus newline, not read and remain on stdin

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Boundary Testing Example (cont.)

- Rewrite the code

```
int i;
char s[MAXLINE];
for (i=0; i<MAXLINE-1; i++)
    if ((s[i] = getchar()) == '\n')
        break;
s[i] = '\0';
```

- Another boundary condition: EOF

```
for (i=0; i<MAXLINE-1; i++)
    if ((s[i] = getchar()) == '\n' || s[i] == EOF)
        break;
s[i] = '\0';
```

- What are other boundary conditions?
  - Nearly full
  - Exactly full
  - Over full

This is wrong. Why?

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Boundary Testing Example (cont.)

- Rewrite yet again

```
for (i=0; ; i++) {
   int c = getchar();
   if (c==EOF || c=='\n' || i==MAXLINE-1) {
              s[i] = '\0';
     break;
   }
   else s[i] = c;
}
```

- There's still a problem...

Input:

```
Four
score and seven
years
```

Output:

```
FourØ
score anØ
 sevenØ
yearsØ
```

Where's the 'd'?

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Ambiguity in Specification

- If line is too long, what should happen?
  - Keep first MAXLINE characters, discard the rest?
  - Keep first MAXLINE-1 characters + '\0' char, discard the rest?
  - Keep first MAXLINE-1 characters + '\0' char, save the rest for the next call to the input function?
- Probably, the specification didn't even say what to do if MAXLINE is exceeded
  - Probably the person specifying it would prefer that unlimited-length lines be handled without any special cases at all
  - Moral: testing has uncovered a design problem, maybe even a specification problem!
- Define what to do
  - Truncate long lines?
  - Save the rest of the text to be read as the next line?

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Morals of This Little Story

- Complicated, messy boundary cases are often symptomatic of bad design or bad specification
- Clean up the specification if you can
- If you can't fix the specification, then fix the code

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Statement Testing

(2) Statement testing

- "Testing to satisfy the criterion that each statement in a program be executed at least once during program testing."
  - Glossary of Computerized System and Software Development Terminology

Statement Testing Example

- Example pseudocode:

```
if (condition1)
   statement1;
else
   statement2;
…
if (condition2)
   statement3;
else
   statement4;
…
```

Statement testing:

Should make sure both "if" statements and all 4 nested statements are executed

- Requires two data sets; example:
  - *condition1* is true and *condition2* is true
    - Executes *statement1* and *statement3*
  - *condition1* is false and *condition2* is false
    - Executes *statement2* and *statement4*

Path Testing

(3) Path testing

- "Testing to satisfy coverage criteria that each logical path through the program be tested. Often paths through the program are grouped into a finite set of classes. One path from each class is then tested."
  - Glossary of Computerized System and Software Development Terminology

- Much more difficult than statement testing
  - For simple programs, can enumerate all paths through the code
  - Otherwise, sample paths through code with random input

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Path Testing Example

- Example pseudocode:

```
if (condition1)
   statement1;
else
   statement2;
…
if (condition2)
   statement3;
else
   statement4;
…
```

Path testing:

Should make sure all logical paths are executed

- Requires four data sets:
  - *condition1* is true and *condition2* is true
  - *condition1* is true and *condition2* is false
  - *condition1* is false and *condition2* is true
  - *condition1* is false and *condition2* is false
- Realistic program => combinatorial explosion!!!

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Stress Testing

(4) Stress testing
- "Testing conducted to evaluate a system or component at or beyond the limits of its specified requirements"
  - Glossary of Computerized System and Software Development Terminology

- What to generate
  - Very large inputs
  - Random inputs (binary vs. ASCII)
- Use computer to generate inputs

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Stress Testing Example 1

- Example program:

```
#include <stdio.h>
int main(void) {
   char c;
   while ((c = getchar()) != EOF)
      putchar(c);
   return 0;
}
```

Stress testing: Should provide **random** (binary and ASCII) inputs

- Intention: Copy all characters of stdin to stdout; but note the bug!!!
- Works for typical (human-generated) ASCII data sets
- Random (computer-generated?) data set containing byte 255 (decimal), alias 11111111 (binary), alias ÿ causes loop to terminate before end-of-file

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Stress Testing Example 2

- Example program:

```
#include <stdio.h>
int main(void) {
   short charCount = 0;
   while (getchar() != EOF)
      charCount++;
   printf("%hd\n", charCount);
   return 0;
}
```

Stress testing: Should provide **very large** inputs

- Intention: Count and print number of characters in stdin
- Works for reasonably-sized data sets
- Fails for (computer-generated?) data set containing more than 32767 characters

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The assert Macro

- An aside…
- The **`assert`** macro
  - One actual parameter, which should evaluate to true or false
  - If true (non-zero):
    - Do nothing
  - If false (zero):
    - Print message to stderr "assert at line x failed"
    - Exit the process

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Uses of assert

- Typical uses of **`assert`**
  - Validate formal parameters

```
size_t Str_getLength(const char *str) {
   assert(str != NULL);
   …
}
```

  - Check for "impossible" logical flow

```
switch (state) {
   case START: … break;
   case COMMENT: … break;
   …
   default: assert(0); /* Never should get here */
}
```

  - Make sure dynamic memory allocation requests worked
    - (Described later in course)

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Disabling asserts

- Problem: **`asserts`** can be time-consuming
  - Want them in code when debugging, but…
  - Might want to remove them from released code
- Bad "solution":
  - When program is finished, delete asserts from code
  - But **`asserts`** are good documentation
  - And in the "real world" no program ever is "finished"!!!
- Solution: Define the **`NDEBUG`** macro
  - Place **`#define NDEBUG`** at top of .c file, before all calls of **`assert`**
  - Makes the **`assert`** macro expand to nothing
  - Essentially, disables asserts

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Disabling asserts (cont.)

- Problem: Awkward to place **`#define NDEBUG`** in only released code
- Solution: Define **`NDEBUG`** when building
  - -D option of gcc defines a macro
  - **`gcc217 -DNDEBUG myfile.c`**
    - Defines **`NDEBUG`** macro in myfile.c, just as if myfile.c contains **`#define NDEBUG`**
- Controversy: Should **`asserts`** be disabled in released code?
  - **`Asserts`** are very time consuming => yes
  - **`Asserts`** are not very time consuming => sometimes unclear
    - Would user prefer (1) exit via assert, or (2) possible data corruption?

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Internal Testing

- Internal testing: Designing your program to test itself
- Internal testing techniques
  - (1) Testing invariants
  - (2) Verifying conservation properties
  - (3) Checking function return values
  - (4) Changing code temporarily
  - (5) Leaving testing code intact
- Let's consider them one at a time…

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Testing Invariants

(1) Testing invariants

- Alias testing pre-conditions and post-conditions
- Some aspects of data structures should not vary
- A function that affects data structure should check those invariants at its leading and trailing edges

- Example: "doubly-linked list insertion" function
  - At leading and trailing edges
    - Traverse doubly-linked list
    - When node x points forward to node y, does node y point backward to node x?

- Example: "binary search tree insertion" function
  - At leading and trailing edges
    - Traverse tree
    - Are nodes are still sorted?

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Testing Invariants (cont.)

- Convenient to use **`assert`** to test invariants

```
#ifndef NDEBUG
int isValid(MyType object) {
   …
   Test invariants here.
   Return 1 (TRUE) if object passes
   all tests, and 0 (FALSE) otherwise.
   …
}
#endif

void myFunction(MyType object) {
   assert(isValid(object));
   …
   Manipulate object here.
   …
   assert(isValid(object));
}
```

Can use NDEBUG in your code, just as **`assert`** does

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Verifying Conservation Properties

(2) Verifying conservation properties

- Generalization of testing invariants
- A function should check affected data structures at leading and trailing edges

- Example: **`Str_concat()`** function
  - At leading edge, find lengths of two given strings; compute sum
  - At trailing edge, find lengths of resulting string
  - Is length of resulting string equal to sum?

- Example: List insertion function
  - At leading edge, find old length of list
  - At trailing edge, find new length of list
  - Does new length equal old length + 1?

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Checking Return Values

(3) Checking function return values

- In Java and C++:
  - Method that detects error can “throw a checked exception”
  - Calling method must handle the exception (or rethrow it)

- In C:
  - No exception-handling mechanism
  - Function that detects error typically indicates so via return value
  - Programmer easily can forget to check return value
  - Programmer (generally) **should** check return value

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Checking Return Values (cont.)

(3) Checking function return values (cont.)

- Example: **`scanf()`** returns number of values read

Bad code

```
int i;
scanf("%d", &i);
```

Good code

```
int i;
if (scanf("%d", &i) != 1)
   /* Error */
```

- Example: **`printf()`** can fail if writing to file and disk is full; returns number of characters (not values) written

Bad code???

```
int i = 100;
printf("%d", i);
```

Good code, or overkill???

```
int i = 100;
if (printf("%d", i) != 3)
   /* Error */
```

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Changing Code Temporarily

(4) Changing code temporarily

- Temporarily change code to generate artificial boundary or stress tests
- Example: Array-based sorting program
  - Temporarily make array very small
  - Does the program handle overflow?
- Remember this for Assignment 3…
- Example: Program that uses a hash table
  - Temporarily make hash function return a constant
  - All bindings map to one bucket, which becomes very large
  - Does the program handle large buckets?

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Leaving Testing Code Intact

(5) Leaving testing code intact
- Leave important testing code in the code
- Maybe surround with `#ifndef NDEBUG … #endif`
- Control with –DNDEBUG gcc option
  - Enables/disables assert macro
  - Also could enable/disable **your** debugging code (see "Testing Invariants" example)

- Beware of conflict:
  - Extensive **internal testing** can lower maintenance costs
  - **Code clarity** can lower maintenance costs
  - But… Extensive **internal testing** can decrease **code clarity!**

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General Testing Strategies

- General testing strategies
  (1) Testing incrementally
  (2) Comparing implementations
  (3) Automation
  (4) Bug-driven testing
  (5) Fault injection

- Let's consider one at a time…

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Testing Incrementally

(1) Testing incrementally

- Test as you write code
  - Add tests as you create new cases
  - Test simple parts before complex parts
  - Test units (i.e., individual modules) before testing the system
- Do regression testing
  - A bug fix often creates new bugs in a large software system, so…
  - Must make sure system has not "regressed" such that previously working functionality now is broken, so…
  - Test all cases to compare the new version with the previous one

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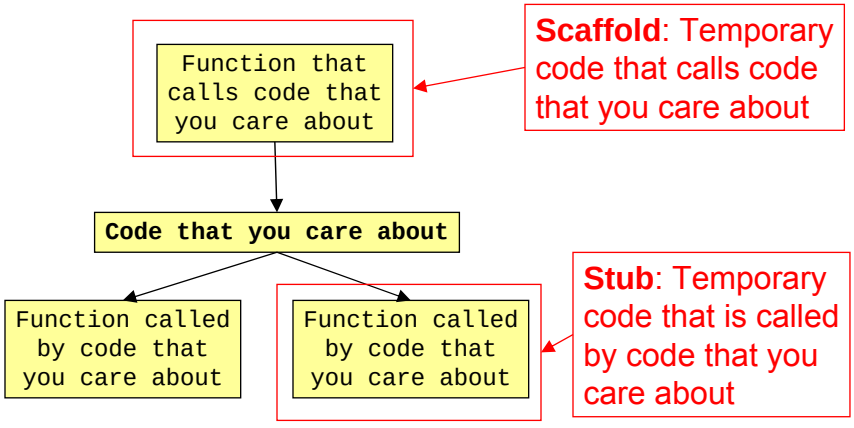
Testing Incrementally (cont.)

(1) Testing incrementally (cont.)

- Create scaffolds and stubs to test the code that you care about



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Comparing Implementations

(2) Compare implementations

- Make sure that multiple independent implementations behave the same
- Example: Compare behavior of your "decomment" vs. "gcc217 –E"
- Example: Compare behavior of your str.h functions vs. standard library string.h functions

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Automation

(3) Automation

- Testing manually is tedious and unreliable, so…
- Create testing code
  - Scripts and data files to test your programs (recall decomment program testing)
  - Software clients to test your modules (recall Str module testing)
- Know what to expect
  - Generate output that is easy to recognize as right or wrong
  - Example: Generate output of **`diff`** command instead of raw program output

- Automated testing can provide:
  - **Much** better coverage than manual testing
  - Bonus: Examples of typical/atypical use for other programmers

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Bug-Driven Testing

(4) Bug-driven testing

- Find a bug => immediately create a test that catches it
- Facilitates regression testing

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Fault Injection

(5) Fault injection

- Intentionally (temporarily) inject bugs!!!
- Then determine if testing finds them
- Test the testing!!!

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Who Tests What

- Programmers
  - White-box testing
  - Pro: An implementer knows all data paths
  - Con: Influenced by how code is designed/written
- Quality Assurance (QA) engineers
  - Black-box testing
  - Pro: No knowledge about the implementation
  - Con: Unlikely to test all logical paths
- Customers
  - Field testing
  - Pros: Unexpected ways of using the software; "debug" specs
  - Cons: Not enough cases; customers don't like "participating" in this process; malicious users exploit the bugs

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Summary

- External testing taxonomy
  - Boundary testing
  - Statement testing
  - Path testing
  - Stress testing
- Internal testing techniques
  - Checking invariants
  - Verifying conservation properties
  - Checking function return values
  - Changing code temporarily
  - Leaving testing code intact

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Summary (cont.)

- General testing strategies
  - Testing incrementally
    - Regression testing
    - Scaffolds and stubs
  - Automation
  - Comparing independent implementations
  - Bug-driven testing
  - Fault injection
- Test the code, the tests – and the specification!

The Rest of This Week

- Reading
  - Required: King book: chapters 8, 9, 11, 12, and 13
  - Recommended: Kernighan and Pike: chapters 5 and 6
  - Recommended: GNU Software: chapter 8
- Assignment #2
  - One-week assignment on String Module
  - Due 9pm Sunday February 22
- Checking your understanding of the first two weeks
  - Try questions 1, 3e, 4, and 6 of the Spring 2008 midterm
  - Questions: http://www.cs.princeton.edu/courses/archive/spring08/cos217/exam1/spring08-cos217-exam1.pdf
  - Answers: http://www.cs.princeton.edu/courses/archive/spring08/cos217/exam1/spring08-cos217-exam1-answers.pdf