Debugging

The material for this lecture is drawn, in part, from The Practice of Programming (Kernighan & Pike) Chapter 5

Goals of this Lecture

• Help you learn about:
  • Strategies and tools for debugging your code

• Why?
  • Debugging large programs can be difficult
  • A power programmer knows a wide variety of debugging strategies
  • A power programmer knows about tools that facilitate debugging
    • Debuggers
    • Version control systems
Testing vs. Debugging

• Testing
  • What should I do to try to **break** my program?

• Debugging
  • What should I do to try to **fix** my program?

Debugging Observations

• Most bugs are reproducible
  • Focus of inspection can be narrowed
  • Narrow by code path or by time

• Bugs are mismatches between expectation & execution
  • Can add more checks on expectations
  • Deviations detected early can prevent bugs

• Program flow can be watched
  • Printing & logging (especially high-volume)
  • Source-level debugging

• Not all bugs visibly manifested
  • But unmanifested bugs still exist
  • Classic cause of “the bug just went away”
  • Nothing ever just “goes away” in a deterministic world
Debugging Heuristics

<table>
<thead>
<tr>
<th>Debugging Heuristic</th>
<th>When Applicable</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Understand error messages</td>
<td>Build-time</td>
</tr>
<tr>
<td>(2) Think before writing</td>
<td></td>
</tr>
<tr>
<td>(3) Look for familiar bugs</td>
<td>Run-time</td>
</tr>
<tr>
<td>(4) Divide and conquer</td>
<td></td>
</tr>
<tr>
<td>(5) Add more internal tests</td>
<td></td>
</tr>
<tr>
<td>(6) Display output</td>
<td></td>
</tr>
<tr>
<td>(7) Use a debugger</td>
<td></td>
</tr>
<tr>
<td>(8) Focus on recent changes</td>
<td></td>
</tr>
</tbody>
</table>

Understand Error Messages

Debugging at **build-time** is easier than debugging at **run-time**, if and only if you...

(1) Understand the error messages!

```c
#include <stdio.h>
int main(void)
/* Print "hello, world" to stdout and return 0. */
{
    printf("hello, world\n");
    return 0;
}
```

What are the error(s)? (No fair looking at the next slide!)
Understand Error Messages (cont.)

(1) Understand the error messages (cont.)

```c
#include <stdio.h>
int main(void)
    /* Print "hello, world" to stdout and return 0. */
    { printf("hello, world\n");
        return 0;
    }
```

Which tool (preprocessor, compiler, or linker) reports the error(s)?

```bash
$ gcc hello.c -o hello
hello.c:1:20: stdio.h: No such file or directory
hello.c:3:1: unterminated comment
hello.c:2: error: syntax error at end of input
```

Understand Error Messages (cont.)

(1) Understand the error messages (cont.)

```c
#include <stdio.h>
int main(void)
    /* Print "hello, world" to stdout and return 0. */
    { printf("hello, world\n");
        return 0;
    }
```

What are the error(s)? (No fair looking at the next slide!)
Understand Error Messages (cont.)

(1) Understand error messages (cont.)

```c
#include <stdio.h>
int main(void)
/* Print "hello, world" to stdout and 
   return 0. */
{
  printf("hello, world\n")
  return 0;
}
```

Which tool (preprocessor, compiler, or linker) reports the error(s)?

```
$ gcc217 hello.c -o hello
hello.c: In function `main':
hello.c:7: error: `retun' undeclared (first use in this function)
hello.c:7: error: (Each undeclared identifier is reported only once
hello.c:7: error: for each function it appears in.)
hello.c:7: error: syntax error before numeric constant
```

What are the error(s)? (No fair looking at the next slide!)
Understand Error Messages (cont.)

(1) Understand error messages (cont.)

```c
#include <stdio.h>
int main(void) /* Print "hello, world" to stdout and return 0. */
{
    printf("hello, world\n")
    return 0;
}
```

Which tool (preprocessor, compiler, or linker) reports the error(s)?

```
$ gcc217 hello.c -o hello
hello.c: In function `main':
hello.c:6: warning: implicit declaration of function `printf'
/tmp/cc43ebjk.o(.text+0x25): In function `main':
: undefined reference to `printf'
collect2: ld returned 1 exit status
```

Understand Error Messages (cont.)

(1) Understand error messages (cont.)

```c
#include <stdio.h>
#define reports
#include <stdlib.h>
enum StateType {
    STATE_REGULAR,
    STATE_INWORD
} int main(int argc, char *argv[]) {
    printf("just hanging around\n");
    return EXIT_SUCCESS;
}
```

What are the error(s)? (No fair looking at the next slide!)
(1) Understand error messages (cont.)

```c
#include <stdio.h>
#include <stdlib.h>
enum StateType { STATE_REGULAR, STATE_INWORD }
int main(int argc, char *argv[]) {
    printf("just hanging around\n");
    return EXIT_SUCCESS;
}
```

What does this error message even mean?

$ gcc217 hello.c -o hello

testen.c:6: error: two or more data types in declaration specifiers

testen.c: In function 'main':
testen.c:6: warning: return type of 'main' is not 'int'

(2) Interpretation tips

- Make sure file's properly indented
- Start at first error message
- Fix first one, recompile, repeat
- Look for missing semicolons, etc.
Think Before Writing

Inappropriate changes could make matters worse, so…

(2) Think before writing
• Draw pictures of the data structures
• Take a break
  • Sleep on it!
  • Start early so you can!!!
• Explain the code to:
  • Yourself
  • Someone else
  • A teddy bear!
  • A giant wookie!!!

Look for Familiar Bugs

(3) Look for familiar bugs
• Some of our favorites:

```c
switch (i) {
    case 0:
        ...
        break;
    case 1:
        ...
    case 2:
        ...
}
```

```c
if (i = 5)

```

```c
if (5 < i < 10)
```

```c
if (i & j)
```

```c
int i;
...
scanf("%d", i);
```

```c
char c;
...
c = getchar();
```

```c
while (c = getchar() != EOF)
```

```c
What are the errors?
```
Look for (Un)Familiar Bugs

(3) Look for (un)familiar bugs

• Some of our favorites:

```c
for (i = 0; i < 10; i++) {
    for (j = 0; j < 10; j++) {
        ...
    }
}
```

```c
for (i = 0; i < 10; i++) {
    for (j = 10; j >= 0; j++) {
        ...
    }
}
```

What are the errors?

Look for Familiar Bugs

(3) Look in familiar places

• Loop start & end conditions → “off by 1” errors
  • Most loop iterations run just fine

• Copy & pasted code
  • Brain sees main idea, not details
  • Details (like variable names) matter

• Check scoping, re-use of variables
  • Compiler complains about uninitialized use, not re-use
  • Prevention: move inside smallest scope possible
Divide and Conquer

(4) Divide and conquer

- Incrementally find smallest/simplest input that illustrates the bug
- Example: Program fails on large input file filex

- Approach 1: Remove input
  - Start with filex
  - Incrementally remove lines of filex until bug disappears
    - Maybe in “binary search” fashion

- Approach 2: Add input
  - Start with small subset of filex
  - Incrementally add lines of filex until bug appears

Divide and Conquer (cont.)

(4) Divide and conquer (cont.)

- Incrementally find smallest code subset that illustrates the bug
- Example: Test client for your module fails

- Approach 1: Remove code
  - Start with test client
  - Incrementally remove lines of test client until bug disappears

- Approach 2: Add code
  - Start with minimal client
  - Incrementally add lines of test client until bug appears
Add More Internal Tests

(5) Add more internal tests

- Internal tests help **find** bugs (see “Testing” lecture)
- Internal test also can help **eliminate** bugs
  - Checking invariants and conservation properties can eliminate some functions from the bug hunt

Display Output

(6) Display output

- Print values of important variables at critical spots
  - Poor:
    ```c
    printf("%d", keyvariable);
    ```
    stdout is buffered; program may crash before output appears
  - Maybe better:
    ```c
    printf("%d\n", keyvariable);
    ```
    Printing ' \n ' flushes the stdout buffer, but not if stdout is redirected to a file
  - Better:
    ```c
    printf("%d", keyvariable);
    fflush(stdout);
    ```
    Call fflush() to flush stdout buffer explicitly
Display Output (cont.)

(6) Display output (cont.)

- Maybe even better:
  ```c
  fprintf(stderr, "%d", keyvariable);
  ```

- Maybe better still:
  ```c
  FILE *fp = fopen("logfile", "w");
  fprintf(fp, "%d", keyvariable);
  fflush(fp);
  ```

  - Write debugging output to `stderr`; debugging output can be separated from normal output via redirection
  - Bonus: `stderr` is unbuffered
  - Write to a log file

Use a Debugger

(7) Use a debugger

- Alternative to displaying output

- Bonuses:
  - Debugger can load “core dumps”
  - Examine state of program when it terminated
  - Debugger can “attach” to a running program
The GDB Debugger

- GNU Debugger
  - Part of the GNU development environment
  - Integrated with Emacs editor
  - Allows user to:
    - Run program
    - Set breakpoints
    - Step through code one line at a time
    - Examine values of variables during run
    - Etc.

- See Appendix 1 for details

Focus on Recent Changes

(8) Focus on recent changes

- Corollary: Debug now, not later

**Difficult:**
(1) Write entire program
(2) Test entire program
(3) Debug entire program

**Easier:**
(1) Write a little
(2) Test a little
(3) Debug a little
(4) Write a little
(5) Test a little
(6) Debug a little
...


Focus on Recent Changes (cont.)

(8) Focus on recent change (cont.)

• Corollary: Maintain old versions

Difficult:
(1) Change code
(2) Note bug
(3) Try to remember what changed since last working version

Easier:
(1) Backup working version
(2) Change code
(3) Note bug
(4) Compare code with working version to determine what changed

Maintaining Previous Versions

• To maintain old versions
  • Approach 1: Manually copy project directory

    $ mkdir myproject
    $ cd myproject
    
    Create project files here.
    
    $ cd ..
    $ cp -r myproject myprojectDateTime
    $ cd myproject
    
    Continue creating project files here.
    ...

• Approach 1.5: use snapshot support in filesystem
• Approach 2: Use RCS…
RCS

Revision Control System
- A simple personal version control system
- Provided with many Linux distributions
  - Available on hats
- Allows developer to:
  - Create a source code repository
  - Check source code files into repository
    - RCS saves old versions
  - Check source code files out of repository
- Appropriate for one-developer projects
- Not appropriate for multi-developer projects
  - Use CVS or Subversion instead
- See Appendix 2 for details

Summary

<table>
<thead>
<tr>
<th>Debugging Heuristic</th>
<th>When Applicable</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Understand error messages</td>
<td>Build-time</td>
</tr>
<tr>
<td>(2) Think before writing</td>
<td>Run-time</td>
</tr>
<tr>
<td>(3) Look for familiar bugs</td>
<td>Run-time</td>
</tr>
<tr>
<td>(4) Divide and conquer</td>
<td>Run-time</td>
</tr>
<tr>
<td>(5) Add more internal tests</td>
<td>Run-time</td>
</tr>
<tr>
<td>(6) Display output</td>
<td>Run-time</td>
</tr>
<tr>
<td>(7) Use a debugger *</td>
<td>Run-time</td>
</tr>
<tr>
<td>(8) Focus on recent changes **</td>
<td>Run-time</td>
</tr>
</tbody>
</table>

* Use GDB
** Use RCS
Appendix 1: Using GDB

• An example program
  File testintmath.c:

```c
#include <stdio.h>

int gcd(int i, int j) {
    int temp;
    while (j != 0) {
        temp = i % j;
        i = j;
        j = temp;
    }
    return i;
}

int lcm(int i, int j) {
    return (i / gcd(i, j)) * j;
}
```

The program is correct

But let’s pretend it has a runtime error in gcd() …

Euclid’s algorithm; Don’t be concerned with details

• General GDB strategy:
  • Execute the program to the point of interest
    • Use breakpoints and stepping to do that
  • Examine the values of variables at that point
Appendix 1: Using GDB (cont.)

• Typical steps for using GDB:

(a) Build with –g
   gcc -g testintmath.c -o testintmath
   • Adds extra information to executable file that GDB uses
(b) Run Emacs, with no arguments
   emacs
(c) Run GDB on executable file from within Emacs
   <Esc key> x gdb <Enter key> testintmath <Enter key>
(d) Set breakpoints, as desired
   break main
   • GDB sets a breakpoint at the first executable line of main()
   break gcd
   • GDB sets a breakpoint at the first executable line of gcd()

Appendix 1: Using GDB (cont.)

• Typical steps for using GDB (cont.):
  (e) Run the program
   run
   • GDB stops at the breakpoint in main()
   • Emacs opens window showing source code
   • Emacs highlights line that is to be executed next
   continue
   • GDB stops at the breakpoint in gcd()
   • Emacs highlights line that is to be executed next
  (f) Step through the program, as desired
   step (repeatedly)
   • GDB executes the next line (repeatedly)
   • Note: When next line is a call of one of your functions:
     • step command steps into the function
     • next command steps over the function, that is, executes the next line
       without stepping into the function
Appendix 1: Using GDB (cont.)

• Typical steps for using GDB (cont.):

(g) Examine variables, as desired
   print i
   print j
   print temp
   • GDB prints the value of each variable
(h) Examine the function call stack, if desired
   where
   • GDB prints the function call stack
   • Useful for diagnosing crash in large program
(i) Exit gdb
   quit
(j) Exit Emacs
   <Ctrl-x key> <Ctrl-c key>

Appendix 1: Using GDB (cont.)

• GDB can do much more:
  • Handle command-line arguments
    run arg1 arg2
  • Handle redirection of stdin, stdout, stderr
    run < somefile > someotherfile
  • Print values of expressions
  • Break conditionally
  • Etc.

• See Programming with GNU Software (Loukides and Oram) Chapter 6
Appendix 2: Using RCS

• Typical steps for using RCS:
  (a) Create project directory, as usual
     ```
     mkdir helloproj
     cd helloproj
     ```
  (b) Create RCS directory in project directory
     ```
     mkdir RCS
     ```
     - RCS will store its repository in that directory
  (c) Create source code files in project directory
     ```
     emacs hello.c ...
     ```
  (d) Check in
     ```
     ci hello.c
     ```
     - Adds file to RCS repository
     - Deletes local copy (don’t panic!)
     - Can provide description of file (1st time)
     - Can provide log message, typically describing changes

Appendix 2: Using RCS (cont.)

• Typical steps for using RCS (cont.):
  (e) Check out most recent version for reading
     ```
     co hello.c
     ```
     - Copies file from repository to project directory
     - File in project directory has read-only permissions
  (f) Check out most recent version for reading/writing
     ```
     co -l hello.c
     ```
     - Copies file from repository to project directory
     - File in project directory has read/write permissions
  (g) List versions in repository
     ```
     rlog hello.c
     ```
     - Shows versions of file, by number (1.1, 1.2, etc.), with descriptions
  (h) Check out a specified version
     ```
     co -l -r versionnumber hello.c
     ```
Appendix 2: Using RCS (cont.)

- RCS can do much more:
  - Merge versions of files
  - Maintain distinct development branches
  - Place descriptions in code as comments
  - Assign symbolic names to versions
  - Etc.
- See *Programming with GNU Software* (Loukides and Oram) Chapter 8

- Recommendation: Use RCS
  - `ci` and `co` can become automatic!

Appendix 3: Debugging Mem Mgmt

- Some debugging techniques are specific to **dynamic memory management**
  - That is, to memory managed by `malloc()`, `calloc()`, `realloc()` and `free()`

- Soon will be pertinent in the course

- For future reference...
Appendix 3: Debugging Mem Mgmt (cont.)

(9) Look for familiar dynamic memory management bugs

- Some of our favorites:

```c
int *p; /* value of p undefined */
    ...
    *p = somevalue;

int *p; /* value of p undefined */
    ...
    fgets(p, 1024, stdin);
```

Dangling pointer

```c
int *p;
    ...
    p = (int*)malloc(sizeof(int));
    ...
    free(p);
    ...
    *p = 5;
```

Dangling pointer

Appendix 3: Debugging Mem Mgmt (cont.)

(9) Look for familiar dynamic memory management bugs (cont.)

- Some of our favorites (cont.):

```c
int *p;
    ...
    p = (int*)malloc(sizeof(int));
    ...
    free(p);
```

Memory leak

- alias

Garbage creation

Detection: Valgrind, etc.

```c
int *p;
    ...
    p = (int*)malloc(sizeof(int));
    ...
    free(p);
    ...
    free(p);
```

Detection: man malloc, MALLOC_CHECK_
Appendix 3: Debugging Mem Mgmt (cont.)

(9) Look for familiar dynamic memory management bugs (cont.)
  • Some of our favorites (cont.):

```c
char *s1 = "Hello";
char *s2;
s2 = (char*)malloc(strlen(s1));
strcpy(s2, s1);
```

Allocating too few bytes

```c
char *s1 = "Hello";
char *s2;
s2 = (char*)malloc(sizeof(s1));
strcpy(s2, s1);
```

Allocating too few bytes

```c
double *p;
p = (double*)malloc(sizeof(double));
```

Allocating too few bytes

(10) Segmentation fault? Make it happen within gdb, and then issue the gdb `where` command. The output will lead you to the line that caused the fault. (But that line may not be where the error resides.)

(11) Manually inspect each call of `malloc()`, `calloc()`, and `realloc()` in your code, making sure that it allocates enough memory.

(12) Temporarily hardcode each call of `malloc()`, `calloc()`, and `realloc()` such that it requests a large number of bytes. If the error disappears, then you'll know that at least one of your calls is requesting too few bytes.
Appendix 3: Debugging Mem Mgmt (cont.)

(13) Temporarily comment-out each call of free() in your code. If the error disappears, then you'll know that you're freeing memory too soon, or freeing memory that already has been freed, or freeing memory that should not be freed, etc.

(14) Use the Meminfo tool. Programs built with gcc217m are much more sensitive to dynamic memory management errors than are programs built with gcc217. So the error might manifest itself earlier, and thereby might be easier to diagnose.