Goals of this Lecture

• 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

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

• Why?
  • Debugging large programs can be difficult
  • Useful to know various debugging strategies and tools
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 and 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

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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)?
(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)?

```
$ 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
```
(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)?
(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)?

```
$ 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
```
(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;
}
```

What are the error(s)?
(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
```
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!!!
(3) Look for familiar bugs

- Some of our favorites:

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

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

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

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

```c
if (i = 5)
    ...
```

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

```c
if (i & 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
(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
(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
(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
(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.
Using GDB: Example Program

- 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;
}
```

... int main(void) {
    int iGcd;
    int iLcm;
    iGcd = gcd(8, 12);
    iLcm = lcm(8, 12);
    printf("%d %d\n", iGcd, iLcm);
    return 0;
}

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

The program is correct

But let’s pretend it has a runtime error in `gcd()` ...
(a) Build with –g
   gcc217 –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()
Using GDB: Stepping Through Code

- 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
Using GDB: Examining Variables

(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>
Using GDB: Sophisticated I/O

• 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
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
...

...
(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!!!
Maintaining Previous Versions

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

```bash
$ 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...
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
Using RCS: Getting Started

(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
Using RCS: Check Out and In

(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`
Using RCS: Fancy Stuff

- 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!
### Summary

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* Use GDB
** Use RCS

See Appendix slides on debugging memory management code…
Appendix: 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: 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;
```

Dangling pointer

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

**Memory leak**
alias
**Garbage creation**

`Detection: Valgrind, etc.`

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

**Multiple free**

`Detection: man malloc, MALLOC_CHECK_`
Appendix: 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: 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.