Building your own C Toolkit: Part 2

Duncan C. White
d.white@imperial.ac.uk

Dept of Computing,
Imperial College London

The handout and tarballs are available on Materials and at:

http://www.doc.ic.ac.uk/~dcw/c-tools-2021/lecture2/

- Last lecture, we introduced the idea of building a C programming toolkit, and covered programmer's editors, make and multi-directory programs.

- Last lecture, we introduced the idea of building a C programming toolkit, and covered programmer's editors, make and multi-directory programs.
- Today, we're going to carry on, and cover:
  - What to do when things go wrong.
  - Debugging: gdb.

- Last lecture, we introduced the idea of building a C programming toolkit, and covered programmer's editors, make and multi-directory programs.
- Today, we're going to carry on, and cover:
  - What to do when things go wrong.
  - Debugging: gdb.
  - Detecting memory leaks: valgrind.

- Last lecture, we introduced the idea of building a C programming toolkit, and covered programmer's editors, make and multi-directory programs.
- Today, we're going to carry on, and cover:
  - What to do when things go wrong.
  - Debugging: gdb.
  - Detecting memory leaks: valgrind.
  - Profiling-led Optimization.

- Last lecture, we introduced the idea of building a C programming toolkit, and covered programmer's editors, make and multi-directory programs.
- Today, we're going to carry on, and cover:
    - What to do when things go wrong.
    - Debugging: gdb.
    - Detecting memory leaks: valgrind.
    - Profiling-led Optimization.
    - Automatic Ruthless Testing.

- Last lecture, we introduced the idea of building a C programming toolkit, and covered programmer's editors, make and multi-directory programs.
- Today, we're going to carry on, and cover:
  - What to do when things go wrong.
  - Debugging: gdb.
  - Detecting memory leaks: valgrind.
  - Profiling-led Optimization.
  - Automatic Ruthless Testing.
- One of the most common things that you will experience with C programming is that your program dies mysteriously with a Segmentation Fault (aka a segfault).
- Why is that?

- Last lecture, we introduced the idea of building a C programming toolkit, and covered programmer's editors, make and multi-directory programs.
- Today, we're going to carry on, and cover:
    - What to do when things go wrong.
    - Debugging: gdb.
    - Detecting memory leaks: valgrind.
    - Profiling-led Optimization.
    - Automatic Ruthless Testing.
- One of the most common things that you will experience with C programming is that your program dies mysteriously with a Segmentation Fault (aka a segfault).
- Why is that?
- Because C assumes you know what you're doing!

- Or..


ATTENTION
Your mother doesn't work here.
Please clean up your own mess!

- Or..

- It's your responsibility to: check that you don't overrun the bounds of an array,

- Or..

- It's your responsibility to: check that you don't overrun the bounds of an array, don't dereference a NULL/bad pointer,

- Or..

- It's your responsibility to: check that you don't overrun the bounds of an array, don't dereference a NULL/bad pointer, and don't write into read-only memory - as in `char *p = "get ready"; *p = 's';` or `strcpy(p,"hello");`

- Our first technique for fixing a broken C program - when it crashes or produces the wrong answers - is to debug it.
- As the Pragmatic Programmers so nearly said: Know a single debugger well.

- Our first technique for fixing a broken C program - when it crashes or produces the wrong answers - is to debug it.
- As the Pragmatic Programmers so nearly said: Know a single debugger well.
- Let's use gdb, the GNU debugger, to understand a problem in `01.string-debug` - a program crashing with a segfault.

- Our first technique for fixing a broken C program - when it crashes or produces the wrong answers - is to debug it.
- As the Pragmatic Programmers so nearly said: Know a single debugger well.
- Let's use gdb, the GNU debugger, to understand a problem in `01.string-debug` - a program crashing with a segfault.
- The `README` in 01.string-debug explains what to do. In summary:
- Recompile all source code with debugging support - add gcc's -g flag to `CFLAGS` in the Makefile and type `make clean all`.

- Our first technique for fixing a broken C program - when it crashes or produces the wrong answers - is to debug it.
- As the Pragmatic Programmers so nearly said: Know a single debugger well.
- Let's use gdb, the GNU debugger, to understand a problem in `01.string-debug` - a program crashing with a segfault.
- The `README` in 01.string-debug explains what to do. In summary:
- Recompile all source code with debugging support - add gcc's -g flag to `CFLAGS` in the Makefile and type `make clean all`.
- Start gdb then run the program, interacting with it until it crashes.
- Now type `where` to see the call frame stack - the sequence of function calls leading to the crash.

- Our first technique for fixing a broken C program - when it crashes or produces the wrong answers - is to debug it.
- As the Pragmatic Programmers so nearly said: Know a single debugger well.
- Let's use gdb, the GNU debugger, to understand a problem in `01.string-debug` - a program crashing with a segfault.
- The `README` in 01.string-debug explains what to do. In summary:
- Recompile all source code with debugging support - add gcc's -g flag to `CFLAGS` in the Makefile and type `make clean all`.
- Start gdb then run the program, interacting with it until it crashes.
- Now type `where` to see the call frame stack - the sequence of function calls leading to the crash.
- Then print out the values and types of variables to see what has gone wrong.
- The `p VARIABLE` command prints out a variable, and the `whatis VARIABLE` command reminds you of it's type.

- In particular, you'll see that the `char *` variable `q` has a corrupt pointer in it: `p q` shows the error: `Cannot access memory at address 0x555500657265`

- In particular, you'll see that the char * variable q has a corrupt pointer in it: `p q` shows the error: `Cannot access memory at address 0x555500657265`
- Next, by printing the addresses of variables `p, q` and `str` (by commands like `p &p` etc), we see that q immediately follows `str` in memory.

- In particular, you'll see that the char * variable q has a corrupt pointer in it: `p q` shows the error: `Cannot access memory at address 0x555500657265`
- Next, by printing the addresses of variables `p, q` and `str` (by commands like `p &p` etc), we see that q immediately follows `str` in memory.
- We can then use gdb's memory dumper to show us the chunk of memory starting at `&str`, using the wonderfully arcane `x/12c &str` command:

```
0x555555755020 <str>:   104 'h' 101 'e' 108 'l' 108 'l' 111 'o' 32 ' '  116 't'104 'h'
0x555555755028 <q>:     101 'e' 114 'r' 101 'e' 0 '\000'
```

- Do you see the problem now?

- In particular, you'll see that the char * variable q has a corrupt pointer in it: `p q` shows the error: `Cannot access memory at address 0x555500657265`
- Next, by printing the addresses of variables `p, q` and `str` (by commands like `p &p` etc), we see that q immediately follows `str` in memory.
- We can then use gdb's memory dumper to show us the chunk of memory starting at `&str`, using the wonderfully arcane `x/12c &str` command:

```
0x555555755020 <str>:   104 'h' 101 'e' 108 'l' 108 'l' 111 'o' 32 ' '  116 't'104 'h'
0x555555755028 <q>:     101 'e' 114 'r' 101 'e' 0 '\000'
```

- Do you see the problem now?
  str is a char [8] but we have copied `"hello there"` into it - more than 8 chars,

- In particular, you'll see that the char * variable q has a corrupt pointer in it: `p q` shows the error: `Cannot access memory at address 0x555500657265`
- Next, by printing the addresses of variables `p`, `q` and `str` (by commands like `p &p` etc), we see that q immediately follows `str` in memory.
- We can then use gdb's memory dumper to show us the chunk of memory starting at `&str`, using the wonderfully arcane `x/12c &str` command:

```
0x555555755020 <str>:   104 'h' 101 'e' 108 'l' 108 'l' 111 'o' 32 ' '  116 't'104 'h'
0x555555755028 <q>:     101 'e' 114 'r' 101 'e' 0 '\000'
```

- Do you see the problem now?
  str is a char [8] but we have copied `"hello there"` into it - more than 8 chars, so the rest of the string ('e', 'r', 'e' and the trailing \0) has OVERFLOWED into the adjacent variable's space, which happens to be q.

- In particular, you'll see that the char * variable q has a corrupt pointer in it: `p q` shows the error: `Cannot access memory at address 0x555500657265`
- Next, by printing the addresses of variables `p, q` and `str` (by commands like `p &p` etc), we see that q immediately follows `str` in memory.
- We can then use gdb's memory dumper to show us the chunk of memory starting at `&str`, using the wonderfully arcane `x/12c &str` command:

```
0x555555755020 <str>:   104 'h' 101 'e' 108 'l' 108 'l' 111 'o' 32 ' '  116 't'104 'h'
0x555555755028 <q>:     101 'e' 114 'r' 101 'e' 0 '\000'
```

- Do you see the problem now?
  str is a char [8] but we have copied `"hello there"` into it - more than 8 chars, so the rest of the string ('e', 'r', 'e' and the trailing \0) has OVERFLOWED into the adjacent variable's space, which happens to be q.
- But q is a char *, so interpreting those overflowing bytes as an address we get 0x555500657265, some arbitrary address in memory. Fortunately, that's not a valid char *, so dereferencing it gave our segfault.

- To find out how the overflow occurred, you can use gdb to set breakpoints, or watch a variable to stop the debugging session each time it changes.

- To find out how the overflow occurred, you can use gdb to set breakpoints, or watch a variable to stop the debugging session each time it changes.
- Let's use the `watch q` command, and then run the program..

- To find out how the overflow occurred, you can use gdb to set breakpoints, or watch a variable to stop the debugging session each time it changes.
- Let's use the `watch q` command, and then run the program.. we find that q was modified accidentally inside `append()`, specifically where we strcat() without checking that the concatenated string fits.

- To find out how the overflow occurred, you can use gdb to set breakpoints, or watch a variable to stop the debugging session each time it changes.
- Let's use the `watch q` command, and then run the program.. we find that q was modified accidentally inside `append()`, specifically where we strcat() without checking that the concatenated string fits.
- The README file suggests an obvious two-part fix for the problem:
  - First, write additional code inside `append()` to detect overflow, and use `assert()` to blow up the program when overflow does occur.
  - Second, prevent overflow from occurring this time - by making `char str[8]` bigger!
- Google for gdb tutorial or gdb cheatsheet for more info.
- Most important, leave gdb by `quit`.

Memory leaks are the most serious C problem:

- Often claimed that 99% of serious C bugs are memory-allocation related.
- C uses pointers and malloc() so much, with so little checking, that debugging memory related problems can be challenging even with gdb.

Memory leaks are the most serious C problem:

- Often claimed that 99% of serious C bugs are memory-allocation related.
- C uses pointers and malloc() so much, with so little checking, that debugging memory related problems can be challenging even with gdb.
- Failing to free() what you malloc() is very bad for long running programs, that continuously modify their data structures.

Memory leaks are the most serious C problem:

- Often claimed that 99% of serious C bugs are memory-allocation related.
- C uses pointers and malloc() so much, with so little checking, that debugging memory related problems can be challenging even with gdb.
- Failing to free() what you malloc() is very bad for long running programs, that continuously modify their data structures.
- Such programs can 'leak' memory until they try to use more memory than the computer has physical RAM, first slowing the computer down a lot, and then either causing it to freeze or your program to crash.

Memory leaks are the most serious C problem:

- Often claimed that 99% of serious C bugs are memory-allocation related.
- C uses pointers and malloc() so much, with so little checking, that debugging memory related problems can be challenging even with gdb.
- Failing to free() what you malloc() is very bad for long running programs, that continuously modify their data structures.
- Such programs can 'leak' memory until they try to use more memory than the computer has physical RAM, first slowing the computer down a lot, and then either causing it to freeze or your program to crash.
- free()ing a block twice is equally dangerous.

Memory leaks are the most serious C problem:

- Often claimed that 99% of serious C bugs are memory-allocation related.
- C uses pointers and malloc() so much, with so little checking, that debugging memory related problems can be challenging even with gdb.
- Failing to free() what you malloc() is very bad for long running programs, that continuously modify their data structures.
- Such programs can ‘leak’ memory until they try to use more memory than the computer has physical RAM, first slowing the computer down a lot, and then either causing it to freeze or your program to crash.
- free()ing a block twice is equally dangerous.
- Dereferencing an uninitialized/reclaimed pointer gives Undefined Behaviour (really hard to debug!).

Memory leaks are the most serious C problem:

- Often claimed that 99% of serious C bugs are memory-allocation related.
- C uses pointers and malloc() so much, with so little checking, that debugging memory related problems can be challenging even with gdb.
- Failing to free() what you malloc() is very bad for long running programs, that continuously modify their data structures.
- Such programs can 'leak' memory until they try to use more memory than the computer has physical RAM, first slowing the computer down a lot, and then either causing it to freeze or your program to crash.
- free()ing a block twice is equally dangerous.
- Dereferencing an uninitialized/reclaimed pointer gives Undefined Behaviour (really hard to debug!).
- Even when you get Seg faults - gdb where (frame stack) may show it crashes in system libraries - but it doesn't really!

To diagnose such problems, we use tools like valgrind:

- Suppose we have a pre-written, pre-tested hash table module, plus a unit test program **testhash**.

To diagnose such problems, we use tools like valgrind:

- Suppose we have a pre-written, pre-tested hash table module, plus a unit test program **testhash**.
- **testhash** creates a single hash table, populates it with keys and values, checks that we can find keys and their associated values, and then iterates over the hash and checks that we see the correct set of (key,value) pairs, then frees the hash table.

To diagnose such problems, we use tools like valgrind:

- Suppose we have a pre-written, pre-tested hash table module, plus a unit test program **testhash**.
- **testhash** creates a single hash table, populates it with keys and values, checks that we can find keys and their associated values, and then iterates over the hash and checks that we see the correct set of (key,value) pairs, then frees the hash table.
- The hash table module passes all tests, and we've even used it in several successful small projects, where each project created a small number of longlived hash tables - so we feel pretty confident that it works!

To diagnose such problems, we use tools like valgrind:

- Suppose we have a pre-written, pre-tested hash table module, plus a unit test program **testhash**.
- **testhash** creates a single hash table, populates it with keys and values, checks that we can find keys and their associated values, and then iterates over the hash and checks that we see the correct set of (key,value) pairs, then frees the hash table.
- The hash table module passes all tests, and we've even used it in several successful small projects, where each project created a small number of longlived hash tables - so we feel pretty confident that it works!
- Now, we intend to embed our hash table in a larger system, we'll need to create, populate and destroy whole hash tables thousands of times.

To diagnose such problems, we use tools like valgrind:

- Suppose we have a pre-written, pre-tested hash table module, plus a unit test program **testhash**.
- **testhash** creates a single hash table, populates it with keys and values, checks that we can find keys and their associated values, and then iterates over the hash and checks that we see the correct set of (key,value) pairs, then frees the hash table.
- The hash table module passes all tests, and we've even used it in several successful small projects, where each project created a small number of longlived hash tables - so we feel pretty confident that it works!
- Now, we intend to embed our hash table in a larger system, we'll need to create, populate and destroy whole hash tables thousands of times.
- The voice of bitter experience: Test that scenario before doing it:-)

To diagnose such problems, we use tools like valgrind:

- Suppose we have a pre-written, pre-tested hash table module, plus a unit test program **testhash**.
- **testhash** creates a single hash table, populates it with keys and values, checks that we can find keys and their associated values, and then iterates over the hash and checks that we see the correct set of (key,value) pairs, then frees the hash table.
- The hash table module passes all tests, and we've even used it in several successful small projects, where each project created a small number of longlived hash tables - so we feel pretty confident that it works!
- Now, we intend to embed our hash table in a larger system, we'll need to create, populate and destroy whole hash tables thousands of times.
- The voice of bitter experience: Test that scenario before doing it:-)
- Write a new test program `iterate N M` that (silently) performs all previous tests N times, sleeping M seconds afterwards.

- Runtime behaviour of `iterate` (with M=0) should be linear with N. Test it with `time ./iterate N 0` for several values of N.

- Runtime behaviour of `iterate` (with M=0) should be linear with N. Test it with `time ./iterate N 0` for several values of N.
- However, we find some strange behaviour around 24k iterations on a 16GB lab machine (eg point07):

- Runtime behaviour of `iterate` (with M=0) should be linear with N. Test it with `time ./iterate N 0` for several values of N.
- However, we find some strange behaviour around 24k iterations on a 16GB lab machine (eg point07): after a few seconds it crashes, saying Killed.
- What's happening?

- Runtime behaviour of `iterate` (with M=0) should be linear with N. Test it with `time ./iterate N 0` for several values of N.
- However, we find some strange behaviour around 24k iterations on a 16GB lab machine (eg point07): after a few seconds it crashes, saying Killed.
- What's happening?
- Try monitoring with `top`, sorting by %age of memory used (run `top -o %MEM`, or use a shell alias: `alias memtop='top -o %MEM'`).

- Runtime behaviour of `iterate` (with M=0) should be linear with N. Test it with `time ./iterate N 0` for several values of N.
- However, we find some strange behaviour around 24k iterations on a 16GB lab machine (eg point07): after a few seconds it crashes, saying Killed.
- What's happening?
- Try monitoring with `top`, sorting by %age of memory used (run `top -o %MEM`, or use a shell alias: `alias memtop='top -o %MEM'`).
- Run iterate with a time delay: `time ./iterate 24000 10` while watching top!

- Runtime behaviour of `iterate` (with M=0) should be linear with N. Test it with `time ./iterate N 0` for several values of N.
- However, we find some strange behaviour around 24k iterations on a 16GB lab machine (eg point07): after a few seconds it crashes, saying Killed.
- What's happening?
- Try monitoring with `top`, sorting by %age of memory used (run `top -o %MEM`, or use a shell alias: `alias memtop='top -o %MEM'`).
- Run iterate with a time delay: `time ./iterate 24000 10` while watching top! iterate's memory use grows rapidly, we see it using 25%, then 50% of memory, then (quite quickly) the process is killed. In the past, it behaved even worse - iterate used over 90% of the memory, and caused the whole system to slow down.

- Runtime behaviour of `iterate` (with M=0) should be linear with N. Test it with `time ./iterate N 0` for several values of N.
- However, we find some strange behaviour around 24k iterations on a 16GB lab machine (eg point07): after a few seconds it crashes, saying Killed.
- What's happening?
- Try monitoring with `top`, sorting by %age of memory used (run `top -o %MEM`, or use a shell alias: `alias memtop='top -o %MEM'`).
- Run iterate with a time delay: `time ./iterate 24000 10` while watching top! iterate's memory use grows rapidly, we see it using 25%, then 50% of memory, then (quite quickly) the process is killed. In the past, it behaved even worse - iterate used over 90% of the memory, and caused the whole system to slow down.
- Hypothesis: the hash table module is leaking some memory each iteration!

- Runtime behaviour of `iterate` (with M=0) should be linear with N. Test it with `time ./iterate N 0` for several values of N.
- However, we find some strange behaviour around 24k iterations on a 16GB lab machine (eg point07): after a few seconds it crashes, saying Killed.
- What's happening?
- Try monitoring with `top`, sorting by %age of memory used (run `top -o %MEM`, or use a shell alias: `alias memtop='top -o %MEM'`).
- Run iterate with a time delay: `time ./iterate 24000 10` while watching top! iterate's memory use grows rapidly, we see it using 25%, then 50% of memory, then (quite quickly) the process is killed. In the past, it behaved even worse - iterate used over 90% of the memory, and caused the whole system to slow down.
- Hypothesis: the hash table module is leaking some memory each iteration! This is a job for valgrind!

- Run `valgrind ./testhash` [back to the simpler test program]

- Run `valgrind ./testhash` [back to the simpler test program]
- The result is:

```
LEAK SUMMARY:
   definitely lost: 520,528 bytes in 2 blocks
...
Rerun with --leak-check=full to see details..
```

- Run `valgrind ./testhash` [back to the simpler test program]
- The result is:

```
LEAK SUMMARY:
   definitely lost: 520,528 bytes in 2 blocks
...
Rerun with --leak-check=full to see details..
```

- Run `valgrind --leak-check=full ./testhash` and you see:

```
260,264 bytes in 1 blocks are definitely lost in loss record 1 of 2
    at 0x4C2FB0F: malloc..
    by 0x108F65: hashCreate (hash.c:73)
    by 0x108C69: main (testhash.c:91)

260,264 bytes in 1 blocks are definitely lost in loss record 2 of 2
    at 0x4C2FB0F: malloc..
    by 0x109059: hashCopy (hash.c:112)
    by 0x108E4C: main (testhash.c:123)
```

- Look at line 73 of `hash.c` in `hashCreate()`, it reads:

  ```
  h->data = (tree *) malloc( NHASH*sizeof(tree) );
  ```

  this is a dynamic array of NHASH sorted binary trees.
- and line 112 is nearly identical in `hashCopy()`.

- Look at line 73 of `hash.c` in `hashCreate()`, it reads:

  ```
  h->data = (tree *) malloc( NHASH*sizeof(tree) );
  ```

  this is a dynamic array of NHASH sorted binary trees.
- and line 112 is nearly identical in `hashCopy()`.
- Now we have to think: Where might we expect to free this "hash data array"?

- Look at line 73 of `hash.c` in `hashCreate()`, it reads:

  ```
  h->data = (tree *) malloc( NHASH*sizeof(tree) );
  ```

  this is a dynamic array of NHASH sorted binary trees.
- and line 112 is nearly identical in `hashCopy()`.
- Now we have to think: Where might we expect to free this "hash data array"? Look in the corresponding `hashFree(hash h)` function.

- Look at line 73 of `hash.c` in `hashCreate()`, it reads:

  ```
  h->data = (tree *) malloc( NHASH*sizeof(tree) );
  ```

  this is a dynamic array of NHASH sorted binary trees.
- and line 112 is nearly identical in `hashCopy()`.
- Now we have to think: Where might we expect to free this "hash data array"? Look in the corresponding `hashFree(hash h)` function.
- Aha! `h->data` is NOT FREED. A simple mistake!
- Add the missing `free(h->data)`, recompile (make).

- Look at line 73 of `hash.c` in `hashCreate()`, it reads:

  ```
  h->data = (tree *) malloc( NHASH*sizeof(tree) );
  ```

  this is a dynamic array of NHASH sorted binary trees.
- and line 112 is nearly identical in `hashCopy()`.
- Now we have to think: Where might we expect to free this "hash data array"? Look in the corresponding `hashFree(hash h)` function.
- Aha! `h->data` is NOT FREED. A simple mistake!
- Add the missing `free(h->data)`, recompile (make).
- Rerun `valgrind ./testhash` and it reports no leaking blocks.
- Run `time ./iterate 24000` again - no non linear behaviour, no weird slowdown.

- Look at line 73 of `hash.c` in `hashCreate()`, it reads:

  ```
  h->data = (tree *) malloc( NHASH*sizeof(tree) );
  ```

  this is a dynamic array of NHASH sorted binary trees.
- and line 112 is nearly identical in `hashCopy()`.
- Now we have to think: Where might we expect to free this "hash data array"? Look in the corresponding `hashFree(hash h)` function.
- Aha! `h->data` is NOT FREED. A simple mistake!
- Add the missing `free(h->data)`, recompile (make).
- Rerun `valgrind ./testhash` and it reports no leaking blocks.
- Run `time ./iterate 24000` again - no non linear behaviour, no weird slowdown.
- Summary: use valgrind regularly while developing your code. Save yourself loads of grief, double your confidence.
- Exercise: does the list example (in Lecture 1's 01.intlist - or any of the later versions) run cleanly with valgrind?

- gcc and most other C compilers can be asked to optimize the code they generate, gcc's options for this are -O, -O2, -O3. Worth trying, rarely makes a significant difference.

- gcc and most other C compilers can be asked to optimize the code they generate, gcc's options for this are -O, -O2, -O3. Worth trying, rarely makes a significant difference.
- What makes far more difference is finding the hot spots using a profiler and selectively optimizing them - by hand. This can produce dramatic speedups, and profiling often (always?) produces surprises.

- gcc and most other C compilers can be asked to optimize the code they generate, gcc's options for this are -O, -O2, -O3. Worth trying, rarely makes a significant difference.
- What makes far more difference is finding the hot spots using a profiler and selectively optimizing them - by hand. This can produce dramatic speedups, and profiling often (always?) produces surprises.
- Let's use the Gnu profiler to profile the bugfixed hash module's iterate test program (in the `03.hash-profile` directory):
  - Add -pg to CFLAGS and LDLIBS in Makefile.
  - Run `make clean all` (compile and link with -pg, which generates instrumented code which tracks function entry and exit times).
  - Run `make profile` to generate a profile, this does 2 things:

- gcc and most other C compilers can be asked to optimize the code they generate, gcc's options for this are -O, -O2, -O3. Worth trying, rarely makes a significant difference.
- What makes far more difference is finding the hot spots using a profiler and selectively optimizing them - by hand. This can produce dramatic speedups, and profiling often (always?) produces surprises.
- Let's use the Gnu profiler to profile the bugfixed hash module's iterate test program (in the `03.hash-profile` directory):
  - Add -pg to CFLAGS and LDLIBS in Makefile.
  - Run `make clean all` (compile and link with -pg, which generates instrumented code which tracks function entry and exit times).
  - Run `make profile` to generate a profile, this does 2 things:
  - First, it runs `./iterate 10000`, which runs slower than normal while profiling, and produces a binary profiling file called gmon.out.
  - Second, gprof analyzes the executable and gmon.out, producing a report showing the top 10 functions (across all their calls) sorted by percentage of total runtime.

- head profile.orig shows results like:

```
  %   cumulative   self              self     total
 time   seconds   seconds    calls  us/call  us/call  name
 27.02      0.61     0.61    20000    30.53    58.06  hashFree
 24.36      1.16     0.55 650660000     0.00     0.00  free_tree
 19.05      1.59     0.43    10000    43.04    43.04  hashCreate
 17.72      1.99     0.40    10000    40.04    67.07  hashCopy
 11.96      2.26     0.27 325330000     0.00     0.00  copy_tree
```

- head profile.orig shows results like:

```
  %   cumulative   self              self     total
 time   seconds   seconds    calls  us/call  us/call  name
 27.02      0.61     0.61    20000    30.53    58.06  hashFree
 24.36      1.16     0.55 650660000     0.00     0.00  free_tree
 19.05      1.59     0.43    10000    43.04    43.04  hashCreate
 17.72      1.99     0.40    10000    40.04    67.07  hashCopy
 11.96      2.26     0.27 325330000     0.00     0.00  copy_tree
```

- Let's divide the number of calls by 10000, to get calls per iteration. 65066 calls to free_tree() and 32533 calls to copy_tree() are suspicious.

- head profile.orig shows results like:

```
  %   cumulative   self              self     total
 time   seconds   seconds    calls  us/call  us/call  name
 27.02      0.61     0.61    20000    30.53    58.06  hashFree
 24.36      1.16     0.55 650660000     0.00     0.00  free_tree
 19.05      1.59     0.43    10000    43.04    43.04  hashCreate
 17.72      1.99     0.40    10000    40.04    67.07  hashCopy
 11.96      2.26     0.27 325330000     0.00     0.00  copy_tree
```

- Let's divide the number of calls by 10000, to get calls per iteration. 65066 calls to free_tree() and 32533 calls to copy_tree() are suspicious. First, 65066 is twice 32533! Does 32533 appear in the code?

- head profile.orig shows results like:

```
 %    cumulative   self              self     total
time    seconds   seconds    calls  us/call  us/call  name
27.02      0.61     0.61     20000    30.53    58.06  hashFree
24.36      1.16     0.55 650660000     0.00     0.00  free_tree
19.05      1.59     0.43     10000    43.04    43.04  hashCreate
17.72      1.99     0.40     10000    40.04    67.07  hashCopy
11.96      2.26     0.27 325330000     0.00     0.00  copy_tree
```

- Let's divide the number of calls by 10000, to get calls per iteration. 65066 calls to free_tree() and 32533 calls to copy_tree() are suspicious. First, 65066 is twice 32533! Does 32533 appear in the code? Aha! the hash table's dynamic array of binary trees has 32533 entries.

- head profile.orig shows results like:

```
  %   cumulative   self              self     total
 time   seconds   seconds    calls  us/call  us/call  name
 27.02      0.61     0.61    20000    30.53    58.06  hashFree
 24.36      1.16     0.55 650660000     0.00     0.00  free_tree
 19.05      1.59     0.43    10000    43.04    43.04  hashCreate
 17.72      1.99     0.40    10000    40.04    67.07  hashCopy
 11.96      2.26     0.27 325330000     0.00     0.00  copy_tree
```

- Let's divide the number of calls by 10000, to get calls per iteration. 65066 calls to free_tree() and 32533 calls to copy_tree() are suspicious. First, 65066 is twice 32533! Does 32533 appear in the code? Aha! the hash table's dynamic array of binary trees has 32533 entries.
- hashFree() and hashCopy() both iterate over the array of trees calling free_tree()/copy_tree() once per tree. The vast majority of these trees are NULL - and both free_tree(t) and copy_tree(t) return immediately if t is NULL.

- head profile.orig shows results like:

```
  %    cumulative   self              self     total
 time   seconds   seconds    calls   us/call   us/call  name
 27.02      0.61     0.61    20000    30.53    58.06  hashFree
 24.36      1.16     0.55 650660000     0.00     0.00  free_tree
 19.05      1.59     0.43    10000    43.04    43.04  hashCreate
 17.72      1.99     0.40    10000    40.04    67.07  hashCopy
 11.96      2.26     0.27 325330000     0.00     0.00  copy_tree
```

- Let's divide the number of calls by 10000, to get calls per iteration. 65066 calls to free_tree() and 32533 calls to copy_tree() are suspicious. First, 65066 is twice 32533! Does 32533 appear in the code? Aha! the hash table's dynamic array of binary trees has 32533 entries.
- hashFree() and hashCopy() both iterate over the array of trees calling free_tree()/copy_tree() once per tree. The vast majority of these trees are NULL - and both free_tree(t) and copy_tree(t) return immediately if t is NULL. How long do hundreds of millions of calls, which immediately return, take?

- head profile.orig shows results like:

```
  %   cumulative   self              self     total
 time   seconds   seconds    calls  us/call  us/call  name
 27.02      0.61     0.61    20000    30.53    58.06  hashFree
 24.36      1.16     0.55 650660000     0.00     0.00  free_tree
 19.05      1.59     0.43    10000    43.04    43.04  hashCreate
 17.72      1.99     0.40    10000    40.04    67.07  hashCopy
 11.96      2.26     0.27 325330000     0.00     0.00  copy_tree
```

- Let's divide the number of calls by 10000, to get calls per iteration. 65066 calls to free_tree() and 32533 calls to copy_tree() are suspicious. First, 65066 is twice 32533! Does 32533 appear in the code? Aha! the hash table's dynamic array of binary trees has 32533 entries.
- hashFree() and hashCopy() both iterate over the array of trees calling free_tree()/copy_tree() once per tree. The vast majority of these trees are NULL - and both free_tree(t) and copy_tree(t) return immediately if t is NULL. How long do hundreds of millions of calls, which immediately return, take?
- We can halve the runtime of iterate by adding `if( h->data[i] != NULL )` conditions on tree calls in hashFree() and hashCopy().

- head profile.orig shows results like:

```
  %   cumulative   self              self     total
 time   seconds   seconds    calls  us/call  us/call  name
 27.02      0.61     0.61    20000    30.53    58.06  hashFree
 24.36      1.16     0.55 650660000     0.00     0.00  free_tree
 19.05      1.59     0.43    10000    43.04    43.04  hashCreate
 17.72      1.99     0.40    10000    40.04    67.07  hashCopy
 11.96      2.26     0.27 325330000     0.00     0.00  copy_tree
```

- Let's divide the number of calls by 10000, to get calls per iteration. 65066 calls to free_tree() and 32533 calls to copy_tree() are suspicious. First, 65066 is twice 32533! Does 32533 appear in the code? Aha! the hash table's dynamic array of binary trees has 32533 entries.
- hashFree() and hashCopy() both iterate over the array of trees calling free_tree()/copy_tree() once per tree. The vast majority of these trees are NULL - and both free_tree(t) and copy_tree(t) return immediately if t is NULL. How long do hundreds of millions of calls, which immediately return, take?
- We can halve the runtime of iterate by adding `if( h->data[i] != NULL )` conditions on tree calls in hashFree() and hashCopy(). Then profile again, a new hotspot may appear. Should we reduce NHASH to some smaller prime number?

- Pragmatic Programmers Tip 62:

  Test Early, Test Often, Test Automatically:
  Tests that run with every build are much more effective than test plans that sit on a shelf.

- Pragmatic Programmers Tip 62:

  > *Test Early, Test Often, Test Automatically:*
  > *Tests that run with every build are much more effective than test plans that sit on a shelf.*

- Test ruthlessly and automatically by building unit test programs (one per module) plus integration tests which test a set of modules together, and overall program tests.
- Add make test target to run the tests. Run them frequently.
- Can run make test whenever you commit a new version into git!

- Pragmatic Programmers Tip 62:

  > *Test Early, Test Often, Test Automatically:*
  > *Tests that run with every build are much more effective than test plans that sit on a shelf.*

- Test ruthlessly and automatically by building unit test programs (one per module) plus integration tests which test a set of modules together, and overall program tests.
- Add make test target to run the tests. Run them frequently.
- Can run make test whenever you commit a new version into git!
- **Most important**: Test programs should check for correct results themselves (essentially, hardcoding the correct answers in them).

- Pragmatic Programmers Tip 62:

  > *Test Early, Test Often, Test Automatically:*
  > *Tests that run with every build are much more effective than test plans that sit on a shelf.*

- Test ruthlessly and automatically by building unit test programs (one per module) plus integration tests which test a set of modules together, and overall program tests.
- Add make test target to run the tests. Run them frequently.
- Can run make test whenever you commit a new version into git!
- **Most important**: Test programs should check for correct results themselves (essentially, hardcoding the correct answers in them).
- If your "test program" simply prints lots of messages out and relies on a human being to read the output, it's **not a proper test program**.

- Pragmatic Programmers Tip 62:

  > *Test Early, Test Often, Test Automatically:*
  > *Tests that run with every build are much more effective than test plans that sit on a shelf.*

- Test ruthlessly and automatically by building unit test programs (one per module) plus integration tests which test a set of modules together, and overall program tests.
- Add make test target to run the tests. Run them frequently.
- Can run make test whenever you commit a new version into git!
- **Most important**: Test programs should check for correct results themselves (essentially, hardcoding the correct answers in them).
- If your "test program" simply prints lots of messages out and relies on a human being to read the output, it's **not a proper test program**.
- Helpful if all tests report in a common style. C doesn't come with a testing infrastructure like Java's jUnit, but it's pretty easy to whip something simple up.

- For example:

```
void testcond( bool ok, char *testname )
{
        printf( "T %s: %s\n", testname, ok?"OK":"FAIL" );
}
```

- testcond() can be used via:

```
intlist l = intlist_nil();
testcond( intlist_kind( l ) == intlist_is_nil,
     "kind(nil) is nil" );

l = intlist_cons( 100, l );
testcond( intlist_kind( l ) == intlist_is_cons,
     "kind([100]) is cons" );
```

- This produces output of the form:

```
T kind(nil) is nil: OK
T kind([100]) is cons: OK
```

- make test could run all test programs in sequence:

```
test:   testprogram1 testprogram2 ...
        ./testprogram1
        ./testprogram2
```

- Or, to show only the test results:

```
        ./testprogram1 | grep ^T
        ./testprogram2 | grep ^T
```

- make test could run all test programs in sequence:

```
test:   testprogram1 testprogram2 ...
        ./testprogram1
        ./testprogram2
```

- Or, to show only the test results:

```
        ./testprogram1 | grep ^T
        ./testprogram2 | grep ^T
```

- Better, we could invoke a simple test framework script with testprograms as arguments, which runs the programs and post-processes the results:

```
test:   testprogram1 testprogram2 ...
        summarisetests ./testprogram1 ./testprogram2
```

- You'll find such a summarisetests Perl script, and `testcond()` in it's own testutils module in the tarball `04.testutils` directory. Go in there and type `make install`, then look inside tarball `05.intlist-with-testing` to see intlist with testing.

Test Driven Development (TDD) writes the test programs before implementing the feature to test.

Test Driven Development (TDD) writes the test programs before implementing the feature to test.

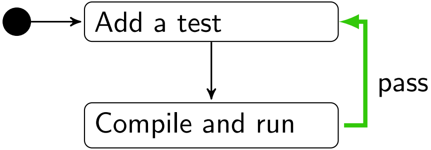
- This helps you focus on one task at a time.
- Encourages incremental development.
- Reduces debugger use.
- (When you find - and fix - a new bug, write a test for it!)
- Don't forget to add some overall tests too.

Test Driven Development (TDD) writes the test programs before implementing the feature to test.

- This helps you focus on one task at a time.
- Encourages incremental development.
- Reduces debugger use.
- (When you find - and fix - a new bug, write a test for it!)
- Don't forget to add some overall tests too.

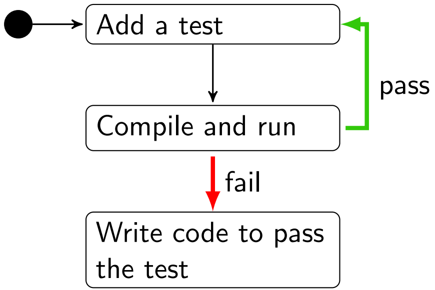
Test Driven Development (TDD) writes the test programs before implementing the feature to test.

- This helps you focus on one task at a time.
- Encourages incremental development.
- Reduces debugger use.
- (When you find - and fix - a new bug, write a test for it!)
- Don't forget to add some overall tests too.



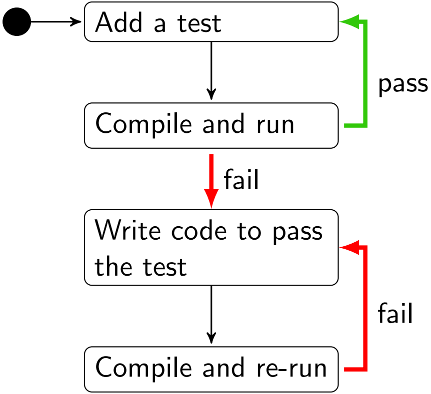
Test Driven Development (TDD) writes the test programs before implementing the feature to test.

- This helps you focus on one task at a time.
- Encourages incremental development.
- Reduces debugger use.
- (When you find - and fix - a new bug, write a test for it!)
- Don't forget to add some overall tests too.



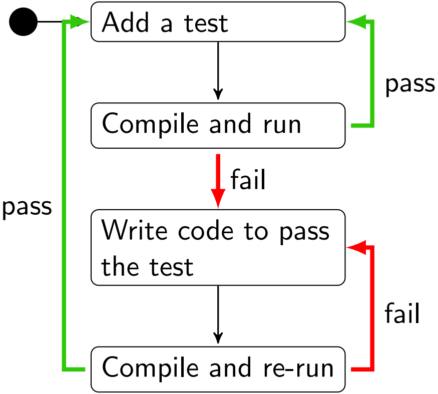
Test Driven Development (TDD) writes the test programs before implementing the feature to test.

- This helps you focus on one task at a time.
- Encourages incremental development.
- Reduces debugger use.
- (When you find - and fix - a new bug, write a test for it!)
- Don't forget to add some overall tests too.



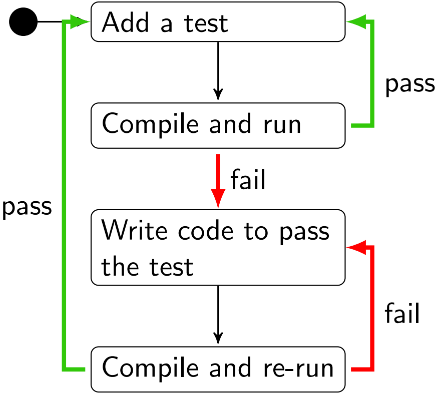
Test Driven Development (TDD) writes the test programs before implementing the feature to test.

- This helps you focus on one task at a time.
- Encourages incremental development.
- Reduces debugger use.
- (When you find - and fix - a new bug, write a test for it!)
- Don't forget to add some overall tests too.



Test Driven Development (TDD) writes the test programs before implementing the feature to test.

- This helps you focus on one task at a time.
- Encourages incremental development.
- Reduces debugger use.
- (When you find - and fix - a new bug, write a test for it!)
- Don't forget to add some overall tests too.



I recommend giving TDD a try, but I'm still concerned as to where the overall design comes in. Rob Chatley will cover TDD in Software Engineering Design next year.