Course "Debugging"

Debugging – An Introduction

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- Universal method of debugging
- 9 rules with subrules and examples ("war stories")

- Rule 1:
  - Understand the system

- Rule 2:
  - Make it fail

- Rule 3:
  - Quit thinking and look
Source

- David J. Agans: "Debugging – The 9 indispensable rules for finding even the most elusive software and hardware problems", Amacom, NY, 2002
  - Only 180 pages
  - A fun read!
Proven Rules

• We will cover 9 generic methodological rules to be used during debugging

• Derived from long experience

• Proven to work:
  • Engineers quickly improve in their debugging skills when they learn to use these rules
  • Most engineers already apply most of the rules
    • more or less precisely, consciously, and consequently
Obvious?

• Most of these rules may look obvious

BUT:
• Obvious does not mean easy
• It is not obvious how to apply them to any one problem
• Often neglected in the "heat of the battle"
• Few people follow all of these rules naturally
  • "Debugging is an art"
Universal

The rules work for
• software
• computer hardware
• other electronics
• cars
• houses
• human bodies
• etc.

• We will focus on software
  • (and more on systems rather than code)
  • but use many examples from other areas as well

The rules work if the system
• has been designed wrong
• has been built wrong
• has been used wrong
• is broken
What the rules are about

The purpose of the rules is to

• help determine the causes of misbehavior (defects)
• help correct the causes of misbehavior

The purpose is not to

• prevent defects ("process management")
• detect the presence of defects ("testing", "use")
• decide whether a defect should be corrected (an aspect of "quality management")
Debugging terminology

(For software only:)

- First the programmer does something wrong, or fails to do something that is required
  - This is called an **error**
  - Errors are events and are performed by humans
- As a result of the error, the software may have incorrect structure
  - This is called a **defect** (or fault)
- As a result of the defect, the software may behave incorrectly when executed
  - This is called a **failure**
- During testing or use, we observe failures and conclude there must be a defect
- **Debugging is primarily about locating the defect**
Tatatataaaa: The nine rules

1. Understand the system
2. Make it fail
3. Quit thinking and look
4. Divide and conquer
5. Change one thing at a time
6. Keep an audit trail
7. Check the plug
8. Get a fresh view
9. If you don't fix it, it ain't fixed
Rule 1: Understand the System

• "It is not so impossible, however, that a man should possess all knowledge which is likely to be useful to him in his work, and this I have endeavoured in my case to do."

Sherlock Holmes
Understand the system: The war story (1)

- **Situation:** A microprocessor-based valve controller, built from a re-used design

- **Problem:** When the scale had a new measurement, the interface chip never passed on an interrupt to the processor
  - Even that was difficult to find out
  - No progress in finding out why
Understand the system:
The war story (2)

- The system:
Understand the system:
The war story (3)

• Critical event: A fellow engineer insisted that the designer reads the entire interface chip data book
  • page 37:
    "The chip will interrupt the microprocessor on the first deselected clock strobe"
  • The design never had deselected clock strobes: a few wires had been saved in the original design
    • as the original system had no interrupts at all
Understand the system: The essence

• You cannot find problems if you do not understand how the system is *supposed* to work

• Essentially, you have to "read the instructions"
  • Preferably *before* things go wrong

• Experience shows that the least understood parts of a complex system invariably have the most problems
  • You need the understanding at *design time*!

• Unfortunately, understanding a complex (software) infrastructure can be extremely time-consuming
  • This is usually the most time-consuming rule to follow
  • But also usually the most worthwhile
Understand the system: Read everything

- Subrule: Read everything, cover to cover
  - The finer the detail you miss, the more difficult the resulting problem

- War story:
  - 3-circuit boards had worked OK for some time
  - 4-circuit boards (otherwise identical) were introduced
  - They failed when they became hot. Nobody knew why.
  - Piece-by-piece comparison found different (but almost equivalent) types of memory chips to be the only difference
  - The design had accommodated all requirements of both types, except one: Wait time between read accesses.
  - The 4-circuit board chips required a longer time
  - (The 3-c. b. chips were also used beyond specification)
Understand the system:
Know your basics

- Subrule: You need to understand the fundamentals of your technology
  - If you do not know what a strobe is, you cannot understand the data book
  - If you do not know what a low-endian word representation is, perfectly clean data may look garbled to you
  - If you specify UTF-8 without knowing what it is, you may never understand why your Umlaut characters do not show up as intended
  - If you understand only vaguely the purpose of methods you call, you will never find the defects in your program's logic
  - etc.
Understand the system: Know the landscape

- Subrule: You need to understand the purpose and interface of all major parts of your system and how they work together
  - Example: While riding your car, there is suddenly a regular tap-tap-tap sound.
  - Candidate parts: Engine, tires, fan
    - To make this list, you need to know your parts and their behavior
  - Diagnosis 1: It is getting faster as you go faster
    - So it is not the fan
  - Diagnosis 2: When you downshift, the tap-tap-tap stays the same
    - So it is not the engine, but the tires
    - To know this, you need to understand transmissions
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Rule 2: Make it fail

- "There is nothing like first-hand evidence."

Sherlock Holmes
Make it fail: What and why

• For efficient debugging, you must be able to reproduce the failure at will
  • You need to find out the exact steps to make it fail

Why you need this:
1. To look at the failure itself
   • and understand its characteristics
2. To be able to focus on finding the cause
   • rather than worry how to make it fail at all
3. So you can tell when you have fixed it
Make it fail: Practical hints

• Do it again
  • After you found out how to make it fail, do it once more to make sure you have the right procedure

• Start at the beginning
  • Make sure you can reproduce the failure from a repeatable (clean) initial state: restart everything from scratch

• Automate
  • If making it fail involves a lot of steps, automate their execution
    • see the war story below
  • If the conditions of the failure are rare, create them artificially
    • e.g. an allergy test by explicitly applying allergens
    • e.g. create heavy-load conditions to provoke a known heavy-load failure
Make it fail: War story (Automation)

• Context: Debugging an analog TV 'Pong' game

• Problem: The ball would sometimes wrongly bounce off the 'practice wall'
  • Manual playing kept attention away from observing the failure

• Automation:
  • Both ball position \((x, y)\) and paddle position \((y)\) were represented by voltages
  • Connect paddle \(y\) to the ball \(y\) voltage and the game will play itself
Make it fail: War story (Stimulation)

- Context: A house

- Problem: A particular window leaks in heavy rain -- but only sometimes

- Stimulation: Create artificial heavy rain by using a hose
  - The leaking happens only when the rain comes from southeast
  - Closely investigating the window finds a break in the caulking at that side of the window
  - After fixing the caulking, another hose test confirms that the defect has been fixed
Make it fail: What if it's intermittent?

- Some failures appear to be irreproducible (intermittent)

- But they aren't:
  - The factors evoking the failure are fixed
    - (remember?: laws of nature!)

- However
  - a. you may not know what the particular factors are
    - and there may be many to choose from
  - b. you may not be able to control those factors
    - or the ones you would like to check for
Make it fail: What if it's intermittent? (2)

If you do not know the relevant factors:
• Try to find *some* relevant factor by trying to make the failure more frequent

• Method: trial-and-error experiments
  • Guess all kinds of conceivable factors
  • Change them and observe
  • If multiple factors are involved, only randomization helps
    • but randomize systematically

• Sometimes making it fail somewhat more often may be the best you can achieve
  • but that may be very helpful
Make it fail:
What if it's still intermittent? (3)

If you cannot control the relevant factors
(or just still don't know them):

- Instrument the system to capture enough information about
  the few failures you get and about normal executions
  - and compare those two kinds
- Systematic differences usually provide the clue for finding and
  fixing the problem

- Problem: How can you make sure you fixed it?
  - You need to find a failure signature: Any run showing these
    conditions will fail
  - Then after your corrections, when you see such a run, but no
    failure, you know you have removed your problem.
Side note:
Never throw away a debugging tool

• You should keep useful ad-hoc debugging aids as if they were part of a product
  • Design them well, implement cleanly and document them
  • Store them in the version control archive etc.

• They may be useful again – even in unexpected ways

• War story:
  • When the TV 'Pong' game was shown to the investor, he asked for a "two practice walls mode"
  • Reason: "For selling this thing, we need a demo mode to be run in the shop windows"
  • Solution: The "robot player" developed as a debug aid
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Rule 3: Quit thinking and look

- "It is a capital mistake to theorize before one has data. Insensibly one begins to twist facts to suit theories, instead of theories to suit facts."

Sherlock Holmes
Quit thinking and look: War story

- PC card with slave microprocessor failed sometimes after the program upload
  - Memory checksum was incorrect
- Several junior engineers were assigned to fix this
- Their first test: Repeated writes into a register on the card microprocessor
  - Result was always correct
Quit thinking and look: War story (2)

• Conclusion: Data transfer into the card works alright
• Next step: Understand the system
  • They analysed the memory interface circuits
  • They found that its timing design was borderline
• They assumed this was the problem
• They worked out an additional "fix-the-timing" circuit
  • That took several months!
Quit thinking and look: War story (3)

- Result: The card failed just as often as before
- Now a senior engineer stepped in and insisted they first see the actual failure
- He hooked up a logic analyzer to the memory bus and observed the results of repeated writes of the following pattern (to subsequent byte addresses): 00 55 AA FF
  - He sometimes found something like 00 55 55 AA FF
- So the writes to the card could be duplicate sometimes
  - He checked the write pulse to the card and found it to have noise which sometimes made it look like two pulses
- In the junior engineers "write register" test, this could not be observed
  - Writing the same value twice to the same register is not a problem
Quit thinking and look: War story (4)
Quit thinking and look: Subrules

- Subrule: See the failure
  - We tend to jump to conclusions when really what we are seeing is the consequence of a failure, not the failure itself
    - The junior engineers never saw the timing fail
- Subrule: See the details
  - Looking once is seldom enough
  - More typically, each looking provides a little more information; you will understand the failure bit by bit
- Subrule: Now you see it, now you don't
  - Seeing the actual low-level failure mechanism will be helpful later on when verifying a fix
- Subrule: Instrument the system
  - Looking from the outside may not be easy or good enough
  - Build observation aids (*instrumentation*) into the system
Quit thinking and look: 
Pump war story

- A person X did a favor to his neighbor P, who was a pump salesman
  - P: "Thanks. If ever you need a new well pump, I'll set you up with the best pump there is."
- While X is on a business trip, his wife W hears a strange new noise: a motor running for a few seconds every few hours.
- She calls P, he listens in and says: "It's the well pump".
- He calls his people and they replace the pump.
  - In the process, the well gets stirred and muddy
- The new pump works nicely (except for the mud)
  - **but the noise is still there as before.**
- Reason: X has left a compressor turned on in the garage

*See the failure!*
Quit thinking and look: Crash war story

- A server computer crashed late every night
  - Always at approximately the same time
- The administrators had restart logs, but no indication of the cause of the crashes
  - They figured it had to be "something automatic"
- They monitored processes for weeks, but found no correlations
- The one decided to stay late to actually observe the failure
  - and sure enough, shortly after 11pm, the computer failed: it lost its power supply
  - Reason: The janitor had pulled the plug, to use the outlet for the vacuum cleaner

See the failure!
Note: Janitor-related problems are fairly common!
Quit thinking and look: Instrument the system

At design time:
- In hardware (or embedded software) add plenty of monitor signals or even sensors or even displays
- In software, add plenty of tracing functionality
  - Preferably configurable at run time
  - Leave most of that in, even in production code
  - Use consistent, structured output formats for simple analysis
  - Always include time stamps

At debug time (ad-hoc instrumentation):
- Make sure the problem is still there after you built in your instrumentation
- Make sure it is still gone after you take it out (if any)
Quit thinking and look: War story

• A video compression software had surprisingly bad image quality on moving objects

• So the programmers analyzed the motion estimation
  • which encodes a moving object as an x/y translation of some part of the previous picture
Quit thinking and look: War story (2)

• They added code that would indicate motion estimation in the video by colored dots
  • Color for direction: down=orange, left=green etc.
  • Brightness for motion magnitude
  • The tests showed much fewer dots for left-right movements than for up-down movements

• They added output of all motion search results
  • and found that only few horizontal positions had matches

• There was a simple coding error in the horizontal search
  See the details!
Quit thinking and look: Instrument the system (2)

- **Sub-subrule: Don't be afraid to dive in**
  - It is often advisable to do some preparation work (such as rebuilding the system with instrumentation put in) rather than try to debug "from the outside"

- **Sub-subrule: Add instrumentation on**
  - If your system is not instrumented (enough), you may be able to view some things at the existing network interfaces,
    - e.g. between application server and database server

- **Instrumentation in daily life**
  - Medicine: add-on (X-ray, ECG, EEG, etc.), built-in (marker genes etc.)
  - Plumbing: gauges (pressure, temperature, fill level), hydrogen sulfide added to natural gas
Quit thinking and look: Heisenberg principle

- The Heisenberg uncertainty principle:
  - When measuring location and momentum of a particle
  - it is impossible to measure both at once arbitrarily precisely
- Meaning (very roughly): It is a law of nature that instrumentation affects the observed system
- This principle often is at work in debugging, too (not literally, though)
  - Debuggers slow down the software and affect timing, change locations of code/data, neighbors, etc.
  - Instrumentation in the code increases code size and perhaps data size
  - Almost any change can influence instable hardware
- Hence, some problems disappear under instrumentation
  - They are often called 'Heisenbugs'
Quit thinking and look: Role of guessing

- The rule proposes looking to be better than guessing
- However, you often cannot get anywhere without guessing
- The rule is
  
  **Guess only to focus the search**
  
  - Positive example: the motion estimation war story
- After guessing you need to confirm your guess
  - Negative example: the pump war story

- There is one case where attempting a fix without confirming the guess may be the right idea:
  - The cause is highly likely and the fix is cheap
    - e.g. a burnt-out light bulb
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Thank you!