Introductory Debugging Techniques

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Software Failures

- January 2018, Tricentis' *Software Fail Watch* documents 606 software failures in CY 2017
  - 3.6 billion people affected
  - $1.7 trillion lost revenue
  - Software failures resulted in 268 years of downtime
  - The number of reported failures was 10 percent higher in 2017 than in 2016
  - Retail and consumer technology industries experienced the most software failures of any industry analyzed

- May 2020, Undo and a Judge Business School MBA project found that
  - Reproducing and fixing a failure takes about 13 hours on average
  - About 26% of developer time is spent reproducing and fixing failures
  - 620M developer hours/year -- $61B salary -- $1.2T enterprise value lost for shareholders

Software Failures

- Radiation overdoses from Therac-25 cause death
  - Race condition
- Ariane 5 explodes at launch ($370m)
  - double to int16 conversion
- Mars climate orbiter burns up in space ($235m)
  - Imperial to metric conversion
- Knight Capital Loses $460m in 45 minutes
  - Dead code, test flag accidentally left enabled
- Boeing 737 MAX MCAS system
  - System component design flaws

Agenda

- What are defects (bugs)?
- What is debugging?
- Challenges when debugging
- A process for debugging
- Some recommendations

Warning! Warning! WARNING!

Opinions lie ahead!

What are defects?

- One common view
  - A software defect (bug) is an *error* in a computer program causes it to produce incorrect or unexpected results, or exhibit unintended behavior

- Another way of thinking about it
  - Each software system is subject to a set of **requirements** that describe its operating environment, inputs, usage, interactions, outputs, and expected behavior
  - These requirements are not always explicitly stated, but are always present
  - A software defect is then a *non-conformity to requirements*
    - Some subset of the system's requirements that are being violated
  - This viewpoint is very common in regulated industries

What is Debugging?

- Wikipedia says:

  "… **debugging** is the process of finding and resolving *bugs* (defects or problems that prevent correct operation) within computer programs, software, or systems."

- Assumptions
  - We understand what *correct operation* means – how do we know that something is actually wrong?
  - We have the ability to observe the programs and/or their output
  - We have the ability to change the underlying source code and other program data
  - We have the ability to build and test the updated programs

Some Terminology

- A *non-conformity* is a failure to meet one or more requirements
- A *defect* (*bug / error / problem*) is incorrect program data (code, input, settings, dependencies, ...) that causes a *non-conformity*
- A *symptom* is observable evidence of a *defect*
- A *deterministic defect* is a *defect* that does not change its *symptoms* under a well-defined set of conditions
- In contrast, a *non-deterministic defect* is a *defect* that changes its *symptoms* from run-to-run under a well-defined set of conditions

Some Terminology

- A *context* is the totality of the environment in which a program that exhibits symptoms is running

- An *analogous context* is one that replicates enough of the original context sufficiently to reproduce a set of *symptoms*

- The *lab* is a setting in which you have total control over the context

- The *field* is a setting where you have minimal or no control over the context

Some Terminology

- A *problem report* describes one or more *symptoms*
- Each *symptom* is caused by one or more *defects (errors, problems)*
- Evidence of a *defect* is made observable by one or more *symptoms*

Debugging Challenges

- Problem reports may be "unhelpful"
  - Misleading / inadequate / incorrect description of symptoms
  - Lack of knowledge about the product – version / configuration / platform / etc.
- Problem reports may not indicate actual problems
  - Sometimes unexpected behavior is not a defect
- Collecting program state data may be difficult
  - Log / settings / crash data could be incomplete, inconclusive, unavailable, non-existent
- Symptoms will probably not indicate the cause
  - The cause and the effect may be distant, in space or time

Debugging Challenges

- Defects and symptoms may be correlated
  - Sometimes symptoms change as repair progresses

- Fixing one defect may introduce new defects
  - Indicative of quick-fixes and/or messy design

- **Symptoms may be difficult to reproduce**
  - Debugging the field is not always possible
  - Constructing an analogous context in the lab is not always feasible
  - Program output is not always available
  - Symptoms from non-deterministic can be especially challenging

The Debugging Process – In Theory

- Characterize and reproduce
  - Determine the surrounding context and observe incorrect behavior
- Locate
  - Find the lines of code responsible for the defect
- Classify
  - Decide what kind of defect you have
- Understand
  - Determine the root cause of the defect and its relationship to the whole
- Repair
  - Resolve the defect without breaking anything else

The Debugging Process – In Theory

- We tend to think of debugging as a simple linear process

```
Product MyJob::Debug(Product const& curr, Problem const& issue)
{
    CharacterizeAndReproduceProblem(curr, issue);

    LocateProblem(curr);

    ClassifyProblem(curr);

    UnderstandProblem(curr);

    Product next = RepairProblem(curr);

    return next;
}
```

A Note on Theory and Practice

- The process appears to make sense, however…

"... in theory there is no difference between theory and practice, while in practice there is"

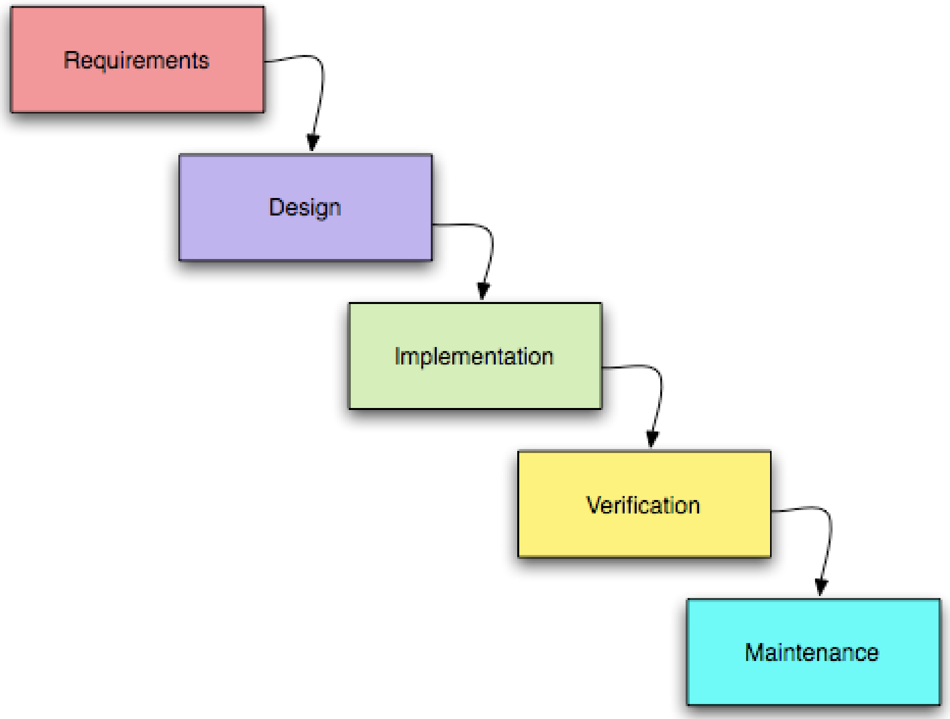
-- *Portfolio: Theory and Practice* by Benjamin Brewster, 1882 February, The Yale Literary Magazine

-- Famously mis-attributed to Yogi Berra, Albert Einstein, Richard Feynman, Walter Savitch, and others

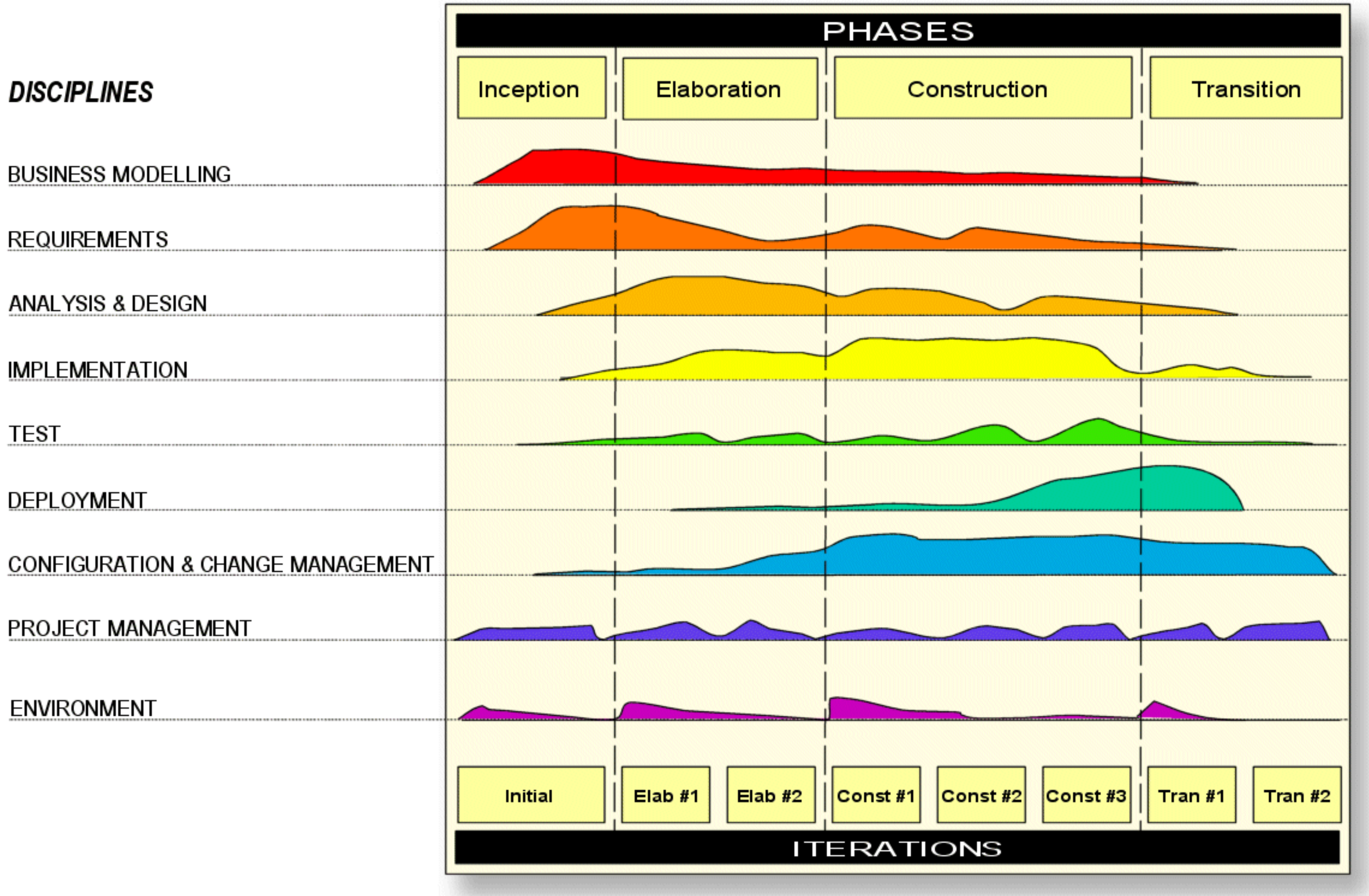
The Debugging Process – In Theory – And Practice

- There's an analogy here with software engineering processes...

Simple cases - waterfall



Complex cases – iterative and incremental



The Debugging Process – In Practice

```
bool MyJob::Debug(Product const& curr, Problem const& issue)
{
    ReviewProblemReport(curr, issue);
    CharacterizeAndReproduceProblem(curr);
    auto  next = Clone(curr);

    while (ReproduceProblem(next) && ResourcesAvailableToRepair(next))
    {
        auto  insight  = async(launch::async, &MyJob::UnderstandProblem, this, next);
        auto  location = async(launch::async, &MyJob::LocateProblem, this, next);
        auto  category = async(launch::async, &MyJob::ClassifyProblem, this, next);
        WaitFor(insight, location, category);

        next = AttemptToRepair(next);
    }

    return (ProblemFixed()) ? Deliver(next), true
                            : PossiblyUpdateResume(), false;
}
```

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Characterizing and Reproducing a Problem

- **Characterizing**
  - Determining the context in which symptoms were observed
  - Version number, platform, resources allocated, external interfaces, configuration data, etc.
  - Information that allows you to instantiate an analogous context

- **Reproducing**
  - Instantiating an analogous context, in the lab, or in the field
  - Running enough of the program (or the system) to observe the reported symptoms
  - Developing new / updating existing test assets to demonstrate the failure
  - Tip: Make sure you're looking at the correct source code!

- Characterizing and reproducing a problem is vital to the debugging process

The Debugging Process – In Practice

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Understand the Problem

- **Understanding**
  - Gaining enough knowledge about a problem and the surrounding code, that you believe you can make changes to carry out a repair

- At a minimum, you should have
  - Located the incorrect lines of code
  - Determined why the code is incorrect – what is the root cause?
  - Determined a proposed classification
  - Formulated a set of proposed changes
  - Determined how your proposed changes would affect the runtime state
  - Determined if your proposed changes would correct the problem

Understand the Problem

- Inspect and verify the associated test assets
  - The test case(s) or harness(es) may be broken
  - If appropriate, test data should demonstrate correct and incorrect behavior
- The defect may not be where you expect it
  - Keep an open mind and be ready to question all parts of the program
- Ask yourself where the defect is *not*
  - Sometimes trying to prove the absence of a defect reveals the defect
- Explain to yourself (or someone else) why there is a defect, and why your proposed fix will resolve the defect
  - A local guru could be helpful

Locate the Problem

- Employ good development practices at the outset
  - Practice iterative, incremental, bottom-up development
  - Add functionality in small sections of code
  - Create test assets for each new increment of functionality
  - Verify that new code doesn't cause previous test cases to fail
  - Verify that new code passes its own test cases
  - Practice defensive programming
- Comments
  - It's much easier to find defects in modular, well-designed code with well-written and extensive test assets
  - Preferably the whole product does this, at a minimum your fixes should

Locate the Problem

- Use trace logging
  - Generating output describing the program state during execution
  - In simpler cases, instrument code with print statements
  - In more complex systems, take advantage of existing logging facilities

- Comments
  - Great way to stay "on the path" when developing new code
  - Usually an easy first step in narrowing down a problem's scope
  - Adds runtime overhead, which can hinder the search for non-deterministic problems

Locate the Problem

- Use debugging and analysis tools
  - Your C++ compiler (*warnings*)
  - Static code analysis tools (*coverity*, *cppcheck*, ...)
  - Interactive debuggers (*gdb*, *lldb*, *msvc*, *udb*, ...)
  - Time-travel debuggers (*gdb*, *rr*, *liverecorder*, *udb*, ...)
  - Sanitizers (*asan*, *tsan*, *ubsan*, ...)
  - Dynamic program analyzers (*valgrind*, *callgrind*, *helgrind*, ...)
  - Call tracers and domain-specific diagnostic tools (*strace*, *wireshark*, *SQL analyzers*...)

- Comments
  - Very powerful tools for deterministic problems
  - Not always useful for non-deterministic problems, especially if runtime overhead is added

Locate the Problem

- Enable and/or add assertions
  - An *assertion* is a facility that evaluates a Boolean predicate at runtime, and causes a serious error (program termination or C++ exception) if the predicate is `false`
  - Verify pre-conditions/post-conditions before/after calling a function
  - Verify class invariants (e.g., in a `self_test()` member function)
  - Verify expected program state

- Comments
  - Usually has little effect on execution speed
  - Good tool for both deterministic and non-deterministic defects
  - Adds some runtime overhead and code complexity

Locate the Problem

- Use backtracking
  - Start where you think the problem occurred and step backward through the code
  - Try to understand the program state at each backward step
- Comments
  - Good for very simple programs and/or small search areas having deterministic problems
  - Easy to do quickly and form a first guess
  - Less effective in complex programs or large search areas
  - Usually ineffective for non-deterministic problems

Locate the Problem

- Divide and conquer (binary search)
  - Pick section of code to examine
  - Place an assertion, or set a breakpoint, halfway through the section
  - If the assertion fires, or the breakpoint is reached with an invalid program state, then the problem is in the first half; otherwise it's in the second half
  - Repeat this halving process until you get to get to a section that reveals the defect
- Comments
  - Trace logging can be used in place of assertions or breakpoints
  - For deterministic problems with a large search area, this is a very powerful technique
  - Not always effective for non-deterministic problems

Locate the Problem

- Problem simplification
  - Gradually and strategically remove (comment out) sections of irrelevant code
  - Can be combined with divide-and-conquer
  - Can be applied to input data as well

- Comments
  - When combined with divide-and-conquer, this is very useful for debugging crashes of release builds as well as non-deterministic problems
  - Work backwards from the end of the section, removing the second half each time

Locate the Problem

- Make the problem worse
  - Vary the context in order to evoke the symptoms (force failures) more frequently

- Comments
  - Figuring out how to make the problem worse is often a helpful first step in finding and understanding the problem
  - Very useful for non-deterministic problems, especially when the symptoms are infrequent

Locate the Problem

- Scientific method
  - Form a hypothesis consistent with observations
  - Implement test(s) to refute the hypothesis
  - If refuted, form a new hypothesis and implement new test(s) to refute it
  - Repeat until your hypothesis cannot be refuted
  - Requires active thinking about the problem

- Comments
  - Effective for all problems
  - Forces you to really understand the code and how program state evolves
  - Is compatible with the other methods of location
  - Can be very time-consuming for unfamiliar code bases

Locate the Problem

- Deterministic problems
  - Review the logs
  - Add assertions where needed to verify invariants
  - If possible, use an interactive debugger, using divide-and-conquer
  - Otherwise, add assertions, using divide-and-conquer

- Non-deterministic problems
  - Review the logs
  - Create a debug build and see if it also exhibits the same symptoms
  - Add assertions where needed to verify invariants
  - Add assertions, and/or comment out code, using divide-and-conquer
  - If needed, make the problem worse
  - If needed, try low-overhead debugging tools

Classifying a Problem

- **Classifying**
  - Determining a defect's *category*
  - Can be useful in formulating a repair strategy
  - Important information in subsequent reviews when considering preventive actions

- Syntax errors
  - Invalid source code – violates the language's grammar
  - In C++, the compiler catches these and issues **errors** (mostly)
  - More of an issue in multi-platform products

- Syntax warnings
  - Basic semantic errors – syntactically valid, but *questionable* code
  - In C++, the compiler issues **warnings**

Classifying a Problem

- Simple source code errors
  - IOW, syntactically correct typos
  - Permit successful builds with latent defects

```
class line_buffer {...};

bool read_line(line_buffer& b);
void parse_line(line_buffer const& b);

void parse_file()
{
    line_buffer  buf;

    while (read_line(buf));
    {
        parse_line(buf);
    }
}
```

Classifying a Problem

- Implementation errors
  - High-level algorithms / data structures / workflows are correct, but
  - Lower-level data structures are used incorrectly
  - Broken invariants, pre-/post-condition violations

- Logic errors
  - High-level algorithms / workflows are logically flawed
  - Mostly correct operation, but fails on corner cases
  - Indicative of design flaws

- Configuration (build) errors
  - Incorrect / invalid binary components are included in a build
  - Result in successful builds that appear to work

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                            : PossiblyUpdateResume(), false;
}
```

Repairing the Problem

- **Repairing**
  - Implementing the *appropriate* set of source code changes that are *necessary* and *sufficient* to resolve the defect
  - Demonstrate resolution by passing tests
- Try to minimize changes to the system – keep changes small and localized
  - Static changes – source code
  - Dynamic changes – program state at runtime
- Verify your repairs against your test assets
  - All new/updated tests should pass
  - All other tests that previously passed must continue to pass

The Debugging Process – In Practice

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```

Delivering the Fix

- **Delivery**
  - Incorporating changes that repair a problem into production code

- Practice good version control
  - Don't include fixes for more than one problem in one commit
  - Don't include extraneous changes (e.g., new features) in fix commits
  - Include new/updated test assets in the fix commits
  - Write commit comments that are clear and concise

- Verify your tests, again
  - Double-check that all new/updated tests pass
  - Double-check that all other tests that previously passed continue to pass

Delivering the Fix

- Create appropriate documentation for posterity
  - How the defect was noticed
  - The conditions under which the defect occurred – the context
  - Steps necessary to reproduce the defect – the analogous context
  - Techniques and tools used to localize the defect
  - The defect's category
  - The underlying root cause of the defect
  - Latent defects precluded by fixing this defect
  - Possible latent defects as yet unaddressed
  - Mistake made and recommendations for preventive actions

- Conduct required reviews (if reviews are part of your SWE process)

Summary / Recommendations

- Practice **defensive programming**
  - Assume the worst case could happen at any time – it usually will

- Employ an appropriate **iterative and incremental development process**
  - Decide what needs to be achieved
  - Formulate a plan for the achievement
  - Understand the invariants, requirements, and context, then design the solution
  - Implement the solution in small, discrete, testable chunks
  - Write code to verify invariants, pre-conditions, post-conditions, and self-test complex components
  - Consider employing the principles of test-driven design
  - Implement test assets in parallel with the solution
  - Employ good configuration management practices everywhere

Summary / Recommendations

- Reproduce the problem!
  - If not in the lab, figure out how to reproduce it in the field

- Learn to use the tools at your disposal
  - Enable C++ compiler warnings
  - Static code analysis tools (*coverity*, *cppcheck*, ...)
  - Interactive debuggers (*gdb*, *lldb*, *msvc*, *udb*, ...)
  - Time-travel debuggers (*gdb*, *rr*, *liverecorder*, *udb*, ...)
  - Sanitizers (*asan*, *tsan*, *ubsan*, ...)
  - Dynamic program analyzers (*valgrind*, *callgrind*, *helgrind*, ...)
  - Call tracers and domain-specific diagnostic tools (*strace*, *wireshark*, *SQL analyzers*...)

Summary / Recommendations

- Try to leave the code better, if only a little
  - Employ defensive programming and a good process, even if only for your repairs
- Don't try to refactor
  - Repair only what needs to be repaired – don't mix repair and refactoring
- Thoroughly document your changes and their justifications
  - Leave breadcrumbs for the next person
- Test your changes – make sure they work!
  - If necessary, create new tests and/or update existing test assets
  - Run existing tests and verify no regressions have been introduced
  - Test in the lab, and if possible, test in the field

Questions? Thank You for Attending!

Talk: `github.com/BobSteagall/CppCon2021`

Blog: `bobsteagall.com`