Software Testing

Algorithm Design & Software Engineering
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Today's Lecture

Objectives

1. Learning debugging strategies in R for finding bugs efficiently
2. Understanding approaches for testing software
3. Formalizing software requirements with the help of unit tests

Outline

Outline

Software Bugs

A software bug is an error or flaw that causes a program to behave in an incorrect or unintended way

Well-known examples

- Ariane 5 flight 501 exploded 40 seconds after launch destroying a $1 billion prototype rocket due to a number overflow
  $\rightarrow$ A 64-bit floating number was converted into a 16-bit integer without exception handling
- Year 2000 bug in which a worldwide collapse was feared
  $\rightarrow$ Years were stored as a two-digit number, making it indistinguishable from 1900
- The 2003 blackout in North America was caused by a race condition which was not handled

Bugs can have various reasons but different counter measures exist

Programming Bug

Example of a buggy code for calculating n^k

```
Power <- 0
for (i in 0:k) {
  power <- power * i
}
```

Question

- Which of the following appear as software bugs in the above snippet?
  - Wrong initialization
  - Wrong loop range
  - Wrong variable naming
  - Wrong variables in mathematical operation
  - Overflow
- No Pingo available

Debugging and Software Testing

Tools to find and prevent bugs

1. Debugging
   - Locates the source for a programming flaw
   - Helps understanding program execution
2. Software testing
   - Standardized means for quality and correctness checks
   - Sometimes used for specifying requirements
   - Assessing the usability of program interfaces

Rule of thumb: debugging consumes about two thirds of the development

Outline

Debugging

- Debugging is recommended when the return value (e. g. of a unit test) is erroneous and the error itself is not obvious
- Tools for examining the control flow and values of variables
- Many programming environments support line-by-line execution debugging, where only one line of code at a time is executed

Debugging strategy

1. Realize that you have a bug
2. Reproduce/generate input values that cause the bug
3. Isolate the flawed component with a binary search
4. Fix it
5. Confirm its successful resolution using the previous input
   $\rightarrow$ When using unit testing: create an automated test

Debugging in R

Key debugging tools in R

1. Output variables to the screen
   → e. g. `print(...)` command or `browser()` for an interactive session
2. Asserts (mostly preventative)
3. Exception handling
4. Using built-in commands in R
   → e. g. `traceback()` for the call stack
5. Interactive debugger inside R Studio

Debugging with Print Commands

One commonly write certain values to the screen for manual inspection

- Show value of a single variable via `print(variable)`
- `print(...)` is necessary to work across all levels of the control flow
- Benefits
  - Easy to use
  - Quick implementation
  - Can narrow down the location of bugs
- Shortcomings
  - Manual checks necessary
  - Identifies only the approximate location of bugs
  - Cannot handle exceptions
- Often combined in practice with a toggle to turn on/off logging messages
- `browser()` switches instead to an interactive session at that point

Debugging with Print Commands

Example: if correct, the loop would print 5, 25 and 125

```
n <- 5
k <- 3

power <- 0
for (i in 0:k) {
  power <- power * i
  print(power) # print current value in each iteration
}

## [1] 0
## [1] 0
## [1] 0
## [1] 0

print(power) # should be 5^3 = 125

## [1] 0
```

Asserts

Trigger a specific message when a condition is not satisfied

- Signal an error if something is wrong (“fail fast”)
- Syntax options
  1. `stop(...)`
  2. `stopifnot(...)`
  3. Package `assertthat`
- Benefits
  - Makes code and errors understandable if something unexpected occurs
  - Easier debugging of functions for other users
- Shortcomings
  - Does not guarantee error-free functions
  - Does not avoid bugs directly
- Often used to check type and range of input to functions

Asserts

Example that checks input types and range

```
cube_root <- function(x) {
  if (class(x) != "numeric") {
    stop("Wrong variable class: not a single number")
  }
  if (x < 0) {
    stop("Wrong range: cannot be less than 0")
  }
  if (!is.finite(x)) {
    stop("Wrong range: cannot be infinite or NA")
  }
  return(x^(1/3))
}
cube_root("error") # should throw an error

## Error in cube_root("error"):  Wrong variable class:  not a single number

cube_root(-5)      # should throw an error

## Error in cube_root(-5):  Wrong range:  cannot be less than 0

cube_root(NA)     # should throw an error

## Error in cube_root(NA): Wrong variable class:  not a single number

cube_root(125)     # 5

## [1] 5
```

Exception Handling

Exception handling (or condition handling) allows program to react upon (un)expected failures

- Functions can throw exceptions when an error occurs
- Code can then handle the exception and react upon it
- Syntax options: `try(...)` and `tryCatch(...)`
- Benefits
  - Program execution can continue even when errors are present
  - Exception can trigger a designated response
  - Helpful technique to interact with packages legacy code
- Shortcomings
  - Helps not to locate unexpected bugs

Exception Handling in R

- `try(...)` ignores an error

```
f.unhandled <- function(x) {
  sqrt(x)
  return(x)
}
# no return value
f.unhandled("string")

## Error in sqrt(x):  non-numeric
argument to mathematical function
```

```
f.try <- function(x) {
  try(sqrt(x))
  return(x)
}
# skips error
f.try("string")

## [1] "string"
```

- Returns an object of `try-error` in case of an exception

```
result <- try(2 + 3)
class(result)

## [1] "numeric"

inherits(result, "try-error")

## [1] FALSE

result

## [1] 5
```

```
error <- try("a" + "b")
class(error)

## [1] "try-error"

inherits(error, "try-error")

## [1] TRUE
```

Exception Handling in R

- `tryCatch(...)` can react differently upon errors, warnings, messages, etc. using handlers

```r
handle_type <- function(expr) {
  tryCatch(expr,
    error=function(e) "error",
    warning=function(e) "warning",
    message=function(e) "message"
  )
}
handle_type(stop("..."))

## [1] "error"

handle_type(warning("..."))

## [1] "warning"

handle_type(message("..."))

## [1] "message"

handle_type(10) # otherwise returns value of input

## [1] 10
```

- R allows to define custom exception types

Call Stack

The call stack shows the hierarchy of function calls leading to the error

- Benefits
  - Shows location of the error
  - Especially helpful with several, nested functions
- Shortcomings
  - Shows where an error occurred but not why
  - Works only for exceptions
- R Studio usage: click “Show Traceback” in R Studio

```
Error in x + "string" : non-numeric argument to binary operator
```

Show Traceback

Rerun with Debug

Example: Call Stack in R

- Code including bug

```
f <- function(x) g(x)
g <- function(x) x + "string"
f(0)
```

- Fired error message

```
## Error in x + "string":  non-numeric argument to binary
operator
```

- Display call stack manually with `traceback()`

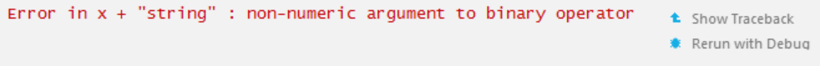
```
traceback()

## 2: f(0)
## 1: g(x)
```

First entry is the hierarchy level, followed by function name and possibly file name and line number

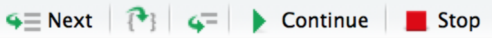
Interactive Debugger in R Studio

Interactive debugging in R Studio allows line-by-line execution

- Benefits
  - Helps finding the location of an error
  - Makes it possible to track changes in the values of all variables
- Shortcomings
  - Can be still time consuming to find location of a bug
- “Rerun with Debug”: repeats execution but stops at the exception



- R Studio toolbar



- Requirements of R Studio: project, file saved, sourced, etc. → see further readings or website for details

Interactive Debugger in R Studio

- Next executes the next statement of up to the current hierarchy level
- steps into the next function including a deeper hierarchy level
- finishes current loop or function
- Continue continues execution to the end of the script
- Stop stops debugging and switches to the coding stage
- Breakpoint stops the execution at a pre-defined point for manual inspection

```
power <- 1
for (i in 1:k) {
  power <- power * n
}
```

→ can be conditional together with an `if`

Debugging

Example: approximate the square root using Newton's method

```
n <- 2
x <- 1
x.old <- NA
while ((x - x.old) >= 10e-5 || is.na(x.old)) {
  x.old <- x
  x <- 1/2 * (x + n/x)
}
x # should be 1.414214, i.e. large error

## [1] 1.416667
```

Question

- Which debugging strategy would you personally prefer?
  - Output variables
  - Asserts
  - Exception handling
  - Insights from call stack
  - Interactive debugger inside R Studio
- No Pingo available

Outline

Software Testing

- Software testing studies the quality of a software
- Provides standardized means and tailored tools for testing
  $\rightarrow$ Opposed to simple “run-and-see”

Reasons

- External proof-of-concept
- Internal quality assurance
- Specifying the requirements and functionality of components

Testing Scope

- Functional (as specified in the requirements)
- Non-functional
  - Usability, graphical appearance
  - Scalability, performance
  - Compatibility, portability
  - Reliability

Testing Perspectives

Testing objectives vary dependent on the perspective

End-users

- Output must match expectations
- Internal code and structure not of relevance
- Mostly black box testing

Developers

- Program must handle all input correctly
- Intermediate values in the code must be correct
- Program needs to work efficiently
- Mostly white box testing

Testing can be

- Static: proofreading, reviews, verification, etc.
- Dynamic: automated unit tests, etc.

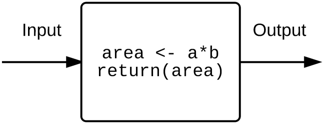
Black Box and White Box Testing

Software testing divided according to the knowledge of a tester

Black box testing

- Tests functionality without any knowledge of the implementation
- Observes the output for a given input
- Testers know what is supposed to come out but not how

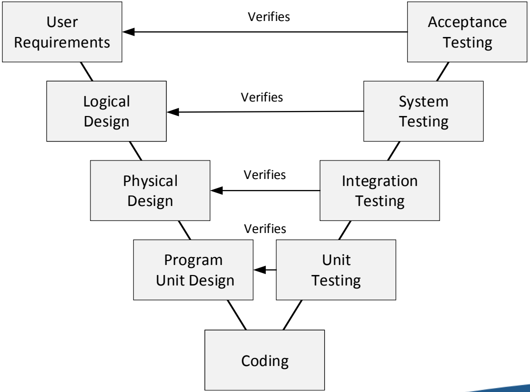
White box testing



- Checks internal implementation of a program
- Tests are designed withknowledge of the code
- Usually automated, e. g. by unit tests

Levels of Testing

- Different level of testing checks the properties of a software
- A designated testing level corresponds to each stage of the waterfall model
- New approach is named V model



Acceptance and System Testing

Acceptance Testing

- Related to usability testing
- Concerns the interaction with users
- Tests e. g. the ease-to-use of the user interface

System Testing

- Performs end-to-end tests of the integrated system
- Tests mainly that requirements are met

Integration Testing

- Ensure the correct interoperability of components
- Thus tests interfaces and interaction above unit testing
- Above unit testing on the scale level, as interaction is tested
- Common in large-scale software projects
  →Example: Windows 7 was deployed daily on 1000+ different PCs to run automated tests

Regression Testing

- Aims is to find bugs after large code changes
- Checks for unintended consequences of changes
- Examples
  - Lost functionality
  - Depreciated features
  - Old bugs that reappeared

Unit Testing

Objectives

- Unit tests focus on the lowest level of a program
- Validates small code segments, e. g. a function or method
- Main use cases
  - Ensure that code matches specification
  - Detect bugs from changing or adding new code

Characteristics

- Each unit test usually consists of multiple simple comparisons
- Focus on boundary values of parameters
- Quick runtimes that allow automated checks after each code change
- Common quality metric is code coverage

Outline

Unit Testing

- Refers to testing the functionality of a specific fragment
- Usually at function or class level
- Tests against pre-defined, expected outcomes

Reasons for using unit testing

- Fewer bugs because automated tests check functionality
- Designing of unit tests enforces better code structure
- Tracks progress of development
- Code becomes more robust since unit tests also control for side effects
- Tests help to document functionality

Unit Testing in R

Package `RUnit`

- Designed for unit testing
- Checks values and exceptions
- Generates text or HTML reports
- Limitation: no test stubs

Package `testthat`

- Supports unit testing, test stubs and test suites
- Generates text output, arbitrarily verbose
- Tests can be automated to run after each file change
- Intended for package development but also works well with simple R scripts

- Similar concepts and usage for both packages
- Code coverage measured for both through additional packages

Test Organization

Tests are organized hierarchically

- **Expectation** verifies a single assumption
  → Checks that given input values return the desired results
- **Tests** (or units) group several expectations
  → Tests a single function for a range of input values (including boundaries such as `NA`)
- **Suites** group several tests
  → In R, this is a simple file
  → For object oriented code, this tests a full class

Unit Testing in R

High-level procedure

1. Store function `f` subject to testing in `f.R`
2. Source that file via `source("f.R")`
3. Create file `test.f.R` that contains the tests
4. Write test, e. g.

```
test_that("Short description", {
  expect_equal(sum(1, 2, 3), 6)
})
```

   where the description should continue "Test that . . . "
5. Load package `testthat`
6. Run file via `test_file("test.f.R")`, or all files in a directory via `test_dir(...)`
7. Assess results, i. e. failed tests

Unit Testing in R

Example calculates roots of quadratic equation $x^2 + px + q$

```
roots_quadratic_eqn <- function(p, q)
{
  if (!is.numeric(p) || !is.numeric(q)) {
    stop("Wrong input format: expects numeric value")
  }
  return(c(-p/2 + sqrt((p/2)^2 - q),
           -p/2 - sqrt((p/2)^2 - q)))
}
```

Unit Testing in R

- Load `testthat` package

```
library(testthat)
```

- Simple test file `test.roots_quadratic_eqn.R`

```
test_that("Roots are numeric and correct", {
  r <- roots_quadratic_eqn(8, 7)
  expect_is(r, "numeric")
  expect_equal(length(r), 2)
  expect_equal(r, c(5, 6))
})
```

- Run tests to compare expected and real results of failed tests

```
test_file("test.roots_quadratic_equation.R")

## ..1
## 1. Failure (at test.roots_quadratic_equation.R#5): Roots are numer
## r not equal to c(5, 6)
## 2/2 mismatches (average diff: 9.5).
## First 2:
##  pos  x y diff
##    1 -1 5   -6
##    2 -7 6  -13
```

Verifying Expectations

- Syntax `expect_*(actual, expected)` ensures expectations
- First argument is the `actual`, the second the `expected` result

Built-in expectation comparisons

- `expect_equal` checks for equality within numerical tolerance

```
expect_equal(1, 1)        # pass
expect_equal(1, 1 + 1e-8) # pass
expect_equal(1, 5)        # expectation fails

## Error:  1 not equal to 5
## 1 - 5 == -4
```

- `expect_identical` checks for exact equality

```
expect_identical(1, 1)        # pass
expect_identical(1, 1 + 1e-8) # expectation fails

## Error:  1 is not identical to 1 + 1e-08.  Differences:
## Objects equal but not identical
```

Verifying Expectations

- `expect_true` and `expect_true` check for `TRUE` and `FALSE` value

```
expect_true(TRUE)  # pass
expect_true(FALSE) # expectation fails

## Error:  FALSE isn't true

expect_true("str") # expectation fails

## Error:  "str" isn't true
```

- `expect_is` checks the class type

```
model <- lm(c(6:10) ~ c(1:5))
expect_is(model, "lm")     # pass
expect_is(model, "class") # expectation fails

## Error:  model inherits from lm not class
```

- `expect_error` checks that an error is thrown

```
expect_error(0 + "str") # pass since error was expected
expect_error(3 + 4)     # expectation fails because of no error

## Error:  3 + 4 code raised an error
```

Stubs and Mocks

- Some functions cannot be be executed for testing purposes, e. g.
  - Functions that access different systems, e. g. online authentication
  - Persistent manipulations of databases
  - Hardware controlling functions, e. g. a robot arm
  - Execution of financial transactions, etc.
  - Functions dependency of non-existent code
- Solution: stubs and mocks

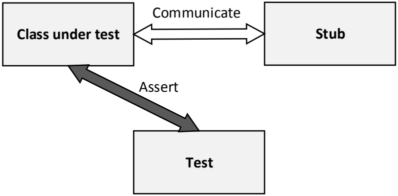
Stubs and Mocks

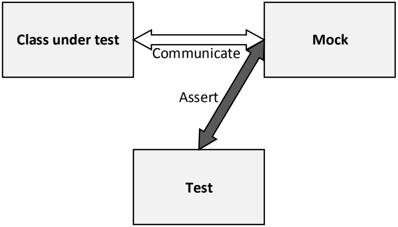
Stubs

- The underlying operation is replaced by a stub for testing
- Stubs can perform primitive operations but usually return only a value

Mocks

- In OOP, replacements for full objects are called mock
- Mocks additionally check if methods were called as expected





Mocks in R

Example

- `calculate_gross(p)` calculates gross price for a VAT of 19 %

```
calculate_gross <- function(net_price) {
  authenticate() # External function call

  if (!is.numeric(net_price)) {
    stop("Input type is not numeric")
  }
  return(round(net_price*1.19, digits=2))
}
```

- Calls external service `authenticate()` to verify the access

```
authenticate <- function() {
  library(RCurl)
  if (getURI("127.0.0.1") != "SUCCESS") {
    stop("Not authenticated")
  }
}
```

- `calculate_gross(p)` can be tested without authentication
  → Need a stub to skip or mimic functionality of `authenticate()`

Stubs in R

- Once can redirect the call `authenticate()` to a stub instead
- In this example, the stub skips authentication

```
authenticate_stub <- function() {
  print("Authentication omitted for testing")
}
```

- Test file `test.calculate_gross.R`

```
test_that('Gross calculation works correctly', {
  with_mock(authenticate = function() {
              print("Authentication omitted for testing")
            },
            expect_equal(calculate_gross(100), 119),
            expect_equal(calculate_gross(70), 83.30),
            expect_error(calculate_gross("str")),
            expect_error(calculate_gross("100.50"))
  )
})
```

Note: the name `with_mock(...)` is misleading since this is not a mock but a stub

Stubs in R

- Run tests with mock

```
test_file("test.calculate_gross.R")
```

```
## [1] "Authentication omitted for testing"
## .[1] "Authentication omitted for testing"
## .[1] "Authentication omitted for testing"
## .[1] "Authentication omitted for testing"
## .
## DONE
```

- Note: `authenticate(p)` needs to exist for `with_mock(...)` to work

Code Coverage

- Code coverage shows to which lines of code are tested
- Helps identifying non-tested code regions
- Usually measures coverage as ratio, e. g. 60 % of all lines, functions, etc.
  → Warning: a high coverage does not guarantee thorough testing
- As a recommendation, focus especially on the boundaries of parameter ranges (0, `NA`, `Inf`, etc.) to identify unhandled problems

R package `covr`

- Supports only coverage when testing full packages
  → Workaround is to create a dummy package

Code Coverage in R

- Load `devtools` and `covr`

```r
library(devtools) # for creating packages
library(covr)     # for code coverage
```

- Create empty package `testcovr` in the current working directory

```r
create("testcovr")          # create default structure
use_testthat("testcovr") # append testing infrastructure
```

- Create sample `absolute_value.R` in folder `testcovr/R/`

```r
absolute_value <- function(x) {
  if (x >= 0) {
    return(x)
  } else {
    return(-x)
  }
}
```

- Create test `test.absolute_value.R` in folder `testcovr/tests/testthat/`

```r
test_that("absolute value is correct", {
  expect_is(absolute_value(-3), "numeric")
  expect_equal(absolute_value(-3), 3)
})
```

Code Coverage in R

- Run all test of package `testcovr`

```
test("testcovr")

## Loading testcovr
## Testing testcovr

## ..
## DONE
```

- Analyze code coverage of package `testcovr`

```
package_coverage("testcovr")

## testcovr Test Coverage:  66.67%
## R\absolute_value.R: 66.67%
```

- Show locations of zero coverage

```
zero_coverage(package_coverage("testcovr"))

##               filename      functions first_line value
## 2 R\\absolute_value.R absolute_value          3     0
```

Code Coverage in R

- Visual reports on code coverage via `shiny`

```r
s <- package_coverage("testcovr")
shine(s)
```

- Overall report

Files | Source

	Coverage	File	Lines	Relevant	Covered	Missed	Hits / Line
R\absolute_value.R	80.00	R\absolute_value.R	7	5	4	1	2

- Coverage line-by-line

```r
absolute_value <- function(x) {
  if (x >= 0) {            2x
    return(x)              !
  } else {                 2x
    return(-x)             2x
  }                        2x
}
```

Summary

Debugging

- Locates bugs or to understand code
- Tools: screen output, asserts, exceptions, interactive debuggers (for call stacks and breakpoints)

Software testing

- Software testing measures quality
- Functional vs. non-functional scope
- Static vs. dynamic testing
- White box vs. black box testing
- V model: acceptance, system, integration and unit testing
- Unit tests
  - Performs automated checks of expectations
  - Measures code coverage
  - Use stubs/mocks to entangle dependencies

Further Readings: Debugging

- Advanced R (CRC Press, 2014, by Wickham)
  Debugging, condition handling, and defensive programmig
  Section 9, pp. 149–171
  `http://adv-r.had.co.nz/Exceptions-Debugging.html`
- Debugging with R Studio
  `https://support.rstudio.com/hc/en-us/articles/205612627-Debugging-with-RStudio`
- Breakpoints in R Studio
  `http://www.rstudio.com/ide/docs/debugging/breakpoint-troubleshooting`
- `assertthat` package documentation at CRAN
  `https://cran.r-project.org/web/packages/assertthat/assertthat.pdf`

Further Readings: Unit Testing

- Testing (by Wickham)

  Book chapter: `http://r-pkgs.had.co.nz/tests.html`

  Slides: `http://courses.had.co.nz/11-devtools/slides/7-testing.pdf`
- testthat: Get Started with TestingR Journal, vol. 3 (1), 2011, by Wickham

  `https://journal.r-project.org/archive/2011-1/RJournal_2011-1_Wickham.pdf`
- `testthat` package documentation at CRAN: `https://cran.r-project.org/web/packages/testthat/testthat.pdf`
- Mocks Aren't Stubs (2007, by Fowler)

  `http://martinfowler.com/articles/mocksArentStubs.html`
- Specialized materials for high-level programming languages, e. g. The Art of Unit Testing (Manning, by Osherove)
- `covr` package documentation at CRAN

  `https://cran.r-project.org/web/packag`