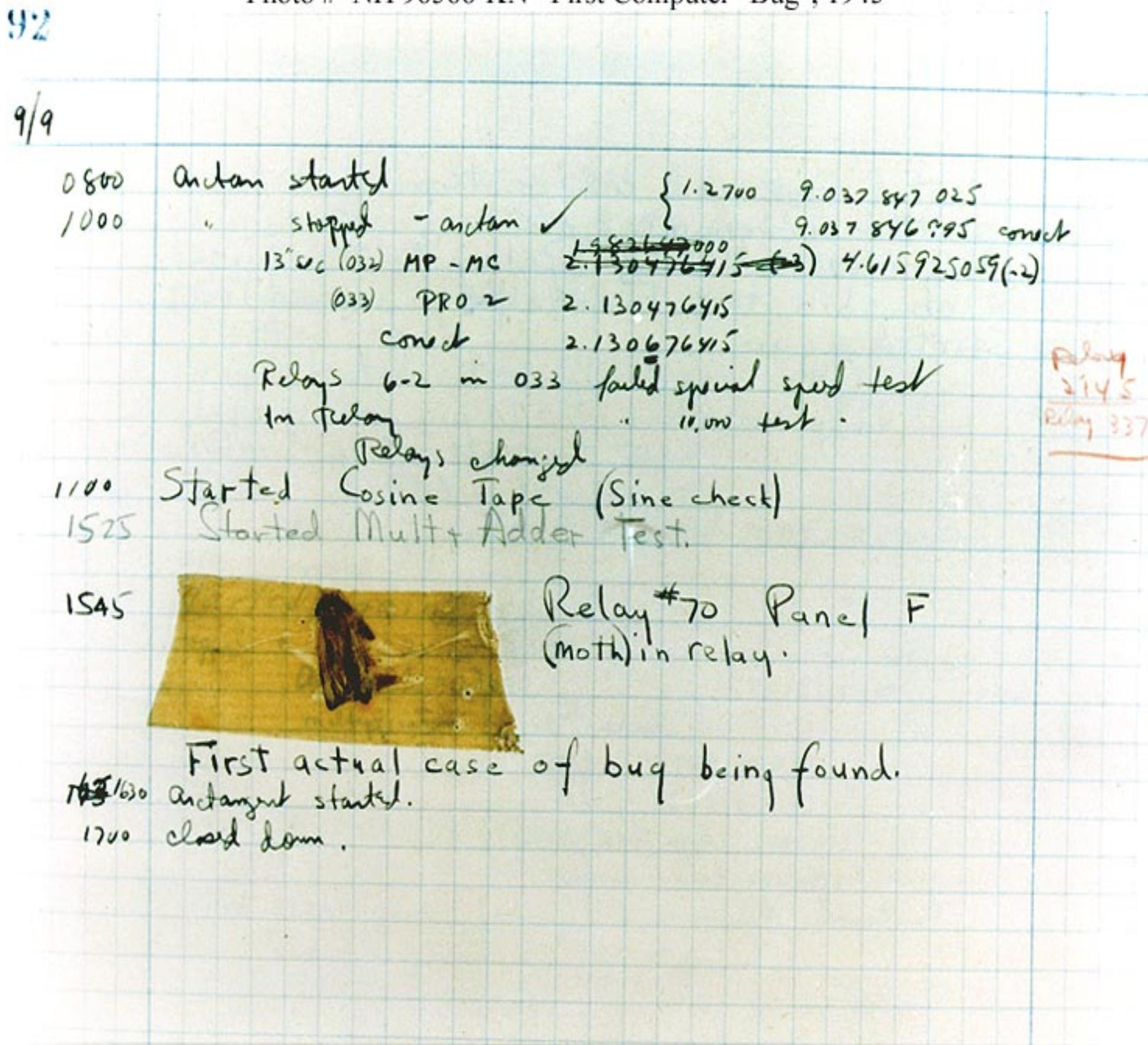
Dependable Software Systems

Topics in Software Testing

Material drawn from [Beizer, Sommerville, Neumann, Mancoridis, Vokolos]

The first "bug"

Photo # NH 96566-KN First Computer "Bug", 1945



The first "bug"

- Moth found trapped between points at Relay #70, Panel F, of the Mark II Aiken Relay Calculator, while it was being tested at Harvard University, September 9, 1945.

`www.history.navy.mil/photos/images/h96000/h96566k.jpg`

Myths About Bugs

- **Benign Bug Hypothesis:** Bugs are nice, tame, and logical.
- **Bug Locality Hypothesis:** A bug discovered within a component affects only that component's behavior.
- **Control Bug Dominance:** Most bugs are in the control structure of programs.
- **Corrections Abide:** A corrected bug remains correct.

Myths About Bugs (Cont'd)

- **Silver Bullets:** A language, design method, environment grants immunity from bugs.
- **Sadism Suffices:** All bugs can be caught using low cunning and intuition.
  (Only easy bugs can be caught this way.)

Defective Software

- We develop programs that contain defects
  - How many? What kind?
- Hard to predict the future, however…
  it is highly likely, that the software we (including you!) will develop in the future will not be significantly better.

Sources of Problems

- **Requirements Definition:** Erroneous, incomplete, inconsistent requirements.
- **Design:** Fundamental design flaws in the software.
- **Implementation:** Mistakes in chip fabrication, wiring, programming faults, malicious code.
- **Support Systems:** Poor programming languages, faulty compilers and debuggers, misleading development tools.

Sources of Problems (Cont'd)

- **Inadequate Testing of Software:** Incomplete testing, poor verification, mistakes in debugging.
- **Evolution:** Sloppy redevelopment or maintenance, introduction of new flaws in attempts to fix old flaws, incremental escalation to inordinate complexity.

Adverse Effects of Faulty Software

- **Communications:** Loss or corruption of communication media, non delivery of data.
- **Space Applications:** Lost lives, launch delays.
- **Defense and Warfare:** Misidentification of friend or foe.

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Adverse Effects of Faulty Software (Cont'd)

- **Transportation:** Deaths, delays, sudden acceleration, inability to brake.
- **Safety-critical Applications:** Death, injuries.
- **Electric Power:** Death, injuries, power outages, long-term health hazards (radiation).

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Adverse Effects of Faulty Software (Cont'd)

- **Money Management:** Fraud, violation of privacy, shutdown of stock exchanges and banks, negative interest rates.
- **Control of Elections:** Wrong results (intentional or non-intentional).
- **Control of Jails:** Technology-aided escape attempts and successes, accidental release of inmates, failures in software controlled locks.
- **Law Enforcement:** False arrests and imprisonments.

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Bug in Space Code

- Project Mercury's FORTRAN code had the following fault:
  - `DO I=1.10` instead of ... `DO I=1,10`
- The fault was discovered in an analysis of why the software did not seem to generate results that were sufficiently accurate.
- The erroneous 1.10 would cause the loop to be executed exactly once!

Military Aviation Problems

- An F-18 crashed because of a missing exception condition:
  `if ... then` ... without the `else` clause that was thought could not possibly arise.
- In simulation, an F-16 program bug caused the virtual plane to flip over whenever it crossed the equator, as a result of a missing minus sign to indicate south latitude.

Year Ambiguities

- In 1992, Mary Bandar received an invitation to attend a kindergarten in Winona, Minnesota, along with others born in '88.
- Mary was 104 years old at the time.

Year Ambiguities (Cont'd)

- Mr. Blodgett's auto insurance rate tripled when he turned 101.
- He was the computer program's first driver over 100, and his age was interpreted as 1.
- This is a double blunder because the program's definition of a teenager is someone under 20!

Dates, Times, and Integers

- The number 32,768 = 2^{15} has caused all sorts of grief from the overflowing of 16-bit words.
- A Washington D.C. hospital computer system collapsed on September 19, 1989, 2^{15} days after January 1, 1900, forcing a lengthy period of manual operation.

Dates, Times, and Integers (Cont'd)

- COBOL uses a two-character date field …
- The Linux **term** program, which allows simultaneous multiple sessions over a single modem dialup connection, died word wide on October 26, 1993.
- The cause was the overflow of an `int` variable that should have been defined as an `unsigned int`.

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Shaky Math

- In the US, five nuclear power plants were shut down in 1979 because of a program fault in a simulation program used to design nuclear reactor to withstand earthquakes.
- This program fault was, unfortunately, discovered after the power plants were built!

Shaky Math (Cont'd)

- Apparently, the arithmetic sum of a set of numbers was taken, instead of the sum of the absolute values.
- The five reactors would probably not have survived an earthquake that was as strong as the strongest earthquake ever recorded in the area.

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Therac-25 Radiation "Therapy"

- In Texas, 1986, a man received between 16,500-25,000 rads in less than 1 sec, over an area of about 1 cm.
- He lost his left arm, and died of complications 5 months later.
- In Texas, 1986, a man received at least 4,000 rads in the right temporal lobe of his brain.
- The patient eventually died as a result of the overdose.

Therac-25 Radiation "Therapy" (Cont'd)

- In Washington, 1987, a patient received 8,000-10,000 rads instead of the prescribed 86 rads.
- The patient died of complications of the radiation overdose.

AT&T Bug: Hello? ... Hello?

- In mid-December 1989, AT&T installed new software in 114 electronic switching systems.
- On January 15, 1990, 5 million calls were blocked during a 9 hour period nationwide.

AT&T Bug (Cont'd)

- The bug was traced to a C program that contained a `break` statement within an `switch` clause nested within a loop.
- The `switch` clause was part of a loop. Initially, the loop contained only `if` clauses with `break` statements to exit the loop.
- When the control logic became complicated, a `switch` clause was added to improve the readability of the code ...

Bank Generosity

- A Norwegian bank ATM consistently dispersed 10 times the amount required.
- Many people joyously joined the queues as the word spread.

Bank Generosity (Cont'd)

- A software flaw caused a UK bank to duplicate every transfer payment request for half an hour. The bank lost 2 billion British pounds!
- The bank eventually recovered the funds but lost half a million pounds in potential interest.

Making Rupee!

- An Australian man purchased $104,500 worth of Sri Lankan Rupees.
- The next day he sold the Rupees to another bank for $440,258.
- The first bank's software had displayed a bogus exchange rate in the Rupee position!
- A judge ruled that the man had acted without intended fraud and could keep the extra $335,758!

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Bug in BoNY Software

- The Bank of New York (BoNY) had a $32 billion overdraft as the result of a 16-bit integer counter that went unchecked.
- BoNY was unable to process the incoming credits from security transfers, while the NY Federal Reserve automatically debited BoNY's cash account.

Bug in BoNY Software (Cont'd)

- BoNY had to borrow $24 billion to cover itself for 1 day until the software was fixed.
- The bug cost BoNY $5 million in interest payments.

Programs and their Environment

- A program's environment is the hardware and systems software required to make it run.
- Programmers should learn early in their careers that it is not smart to blame the environment for bugs.
- Bugs in the environment are rare because most bugs have been found over a long period of usage by a large number of users.

SE Community Response

- Improved environments for software development.
- Better processes to ensure that *we are building the right thing*.
- Technology to help us ensure that we *built the thing right*.

Arsenal for Dependable Software

- Automated development aids
- Static source code and design analysis
- Formal methods
  - Requirements specification, Program Verification
- Inspections
- Peer reviews
- Testing

Software Testing

- Software testing is a critical element of software quality assurance and represents the ultimate review of:
  - specification
  - design
  - coding
- Software life-cycle models (*e.g.*, waterfall) frequently include software testing as a separate phase that follows implementation!

Software Testing (Cont'd)

- Contrary to life-cycle models, testing is an activity that must be carried out throughout the life-cycle.
- It is not enough to test the end product of each phase. Ideally, testing occurs during each phase.

Terminology

- **<u>Error:</u>** A measure of the difference between the actual and the ideal.
- **<u>Fault:</u>** A condition that causes a system to fail in performing its required function.
- **<u>Failure:</u>** The inability of a system or component to perform a required function according to its specifications.
- **<u>Debugging:</u>** The activity by which faults are identified and rectified.

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Terminology

- **<u>Test case:</u>** Inputs to test the program and the predicted outcomes (according to the specification). Test cases are formal procedures:
  - inputs are prepared
  - outcomes are predicted
  - tests are documented
  - commands are executed
  - results are observed and evaluated

  Note: all of these steps are subject to mistakes.

- When does a test "succeed"? "fail"?

Terminology

- **Test suite**: A collection of test cases
- **Testing oracle:** A mechanism (a program, process, or body of data) which helps us determine whether the program produced the correct outcome.
  - Oracles are often defined as a set of input/expected outcome pairs.

Terminology: Sources of Testing Oracles

- **Regression Test Suites:** Test software using the test suites developed for previous versions of the same software.
- **Purchased Test Suites:** Highly standardized software (compilers, mathematical routines) often have commercially available test suites.
- **Existing Program:** A working, trusted, program that is being re-hosted to a new language or O/S.

Terminology

- **<u>Outcome</u>**: What we expect to happen as a results of the test. In practice, *outcome* and *output* may not be the same.
  - For example, the fact that the screen did not change as a result of a test is a tangible *outcome* although there is not *output*.

  In testing we are concerned with outcomes, not just outputs.
- If the predicted and actual outcome match, can we say that the test has passed?

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Terminology

- Strictly speaking -- NO !

- <u>**Coincidental correctness**</u>: A program is said to be coincidentally correct if the test results in the expected outcome, even though the program performs the incorrect computation.

  Example: A program is to calculate $y = x^2$.
  It is incorrectly programmed as $y = 2x$, and it is tested with the input value $x = 2$.

Expected Outcome

- Some times, specifying the expected outcome for a given test case can be tricky business!
  - For some applications we might not know what the outcome should be.
  - For other applications the developer might have a misconception
  - Finally, the program may produced too much output to be able to analyze it in a reasonable amount of time.
  - In general, this is a fragile part of the testing activity, and can be very time consuming.
  - In practice, this is an area with a lot of hand-waving.
  - When possible, automation should be considered as a way of specifying the expected outcome, and comparing it to the actual outcome.

Software Testing Myths

- If we were really good at programming, there would be no bugs to catch.
- There are bugs because we are bad at what we do.
- Testing implies an admission of failure.
- Tedium of testing is a punishment for our mistakes.

Software Testing Myths (Cont'd)

- All we need to do is:
  - concentrate
  - use structured programming
  - use OO methods
  - use a good programming language
  - ...

Software Testing Reality

- Human beings make mistakes, especially when asked to create complex artifacts such as software systems.
- Studies show that even good programs have 1-3 bugs per 100 lines of code.
- People who claim that they write bug-free software probably haven't programmed much.

Goals of Testing

- Discover and prevent bugs.
- The act of designing tests is one of the best bug preventers known.
  - Test, then code philosophy
- The thinking that must be done to create a useful test can discover and eliminate bugs in all stages of software development.
- However, bugs will always slip by, as even our test designs will sometimes be buggy.

The Significance of Testing

- Most widely-used activity for ensuring that software systems satisfy the specified requirements.
- Consumes substantial project resources. Some estimates: ~50% of development costs
- NIST Study: The annual national cost of inadequate testing can be as much as $59B.

[IEEE Software Nov/Dec 2002]

Limitations of Testing

- Testing cannot occur until after the code is written.
- The problem is big!
- Perhaps the least understood major SE activity.
- *Exhaustive testing* is not practical even for the simplest programs. WHY?
- Even if we "exhaustively" test all execution paths of a program, we cannot guarantee its correctness.
  - The best we can do is *increase our confidence!*
- "*Testing can show the presence of bug, not their absence*." EWD

Limitations of Testing

- Testers do not have immunity to bugs.
- Even the slightest modifications – after a program has been tested – invalidate (some or even all of) our previous testing efforts.
- Automation is critically important.
- Unfortunately, there are only a few good tools, and in general, effective use of these good tools is very limited.

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Phases in a Testers Mental Life

- Testing *is* debugging.
- The purpose of testing is to show that the software works.
- The purpose of testing is to show that the software doesn't work.
- The purpose of testing is to reduce the risk of failure to an acceptable level.

Testing Isn't Everything

- Other methods for improving software reliability are:
  - **<u>Inspection methods:</u>** Walkthroughs, formal inspections, code reading.
  - **<u>Design style</u>**: Criteria used by programmers to define what they mean by a "good program".
  - **<u>Static analysis:</u>** Compilers take over mundane tasks such as type checking.
  - **<u>Good Programming Languages and Tools:</u>** Can help reduce certain kinds of bugs (*e.g.*, Lint).

Testing Versus Debugging

- The **purpose of testing** is to show that a program has bugs.
- The **purpose of debugging** is to find the faults that led to the program's failure and to design and implement the program changes that correct the faults.
- Testing is a demonstration of failure or apparent correctness.
- Debugging is a deductive process.

Testing Versus Debugging (Cont'd)

- Testing proves a programmer's failure.
- Debugging is a programmer's vindication.
- Testing can be automated to a large extent.
- Automatic debugging is still a dream.
- Much of testing can be done without design knowledge (by an outsider).
- Debugging is impossible without detailed design knowledge (by an insider).

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Designer Versus Tester (Cont'd)

- The more the tester knows about the design, the more likely he will eliminate useless tests (functional differences handled by the same code).
- Testers that have design knowledge may have the same misconceptions as the designer.

Designer Versus Tester (Cont'd)

- Lack of design knowledge may help the tester to develop test cases that a designer would never have thought of.
- Lack of design knowledge may result in inefficient testing and blindness to missing functions and strange cases.

Program Testing

- A successful test is a test which discovers one or more faults.
- Only validation technique for non-functional requirements.
- Should be used in conjunction with static verification.

Defect Testing

- The objective of defect testing is to discover defects in programs.
- A successful defect test is a test which causes a program to behave in an anomalous way.
- Tests show the presence not the absence of defects.

Testing Priorities

- Only exhaustive testing can show a program is free from defects. However, exhaustive testing is impossible.
- Tests should exercise a system's capabilities rather than its components.
- Testing old capabilities is more important than testing new capabilities.
- Testing typical situations is more important than boundary value cases.

Test Data and Test Cases

- ***Test data***: Inputs which have been devised to test the system.
- ***Test cases:*** Inputs to test the system and the predicted outputs from these inputs if the system operates according to its specification

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Testing Effectiveness

- In an experiment, black-box testing was found to be more effective than structural testing in discovering defects.

White- and Black-box Testing

- **White-box (Glass-box or Structural) testing**: Testing techniques that use the source code as the point of reference for test selection and adequacy.
  - a.k.a. program-based testing, structural testing

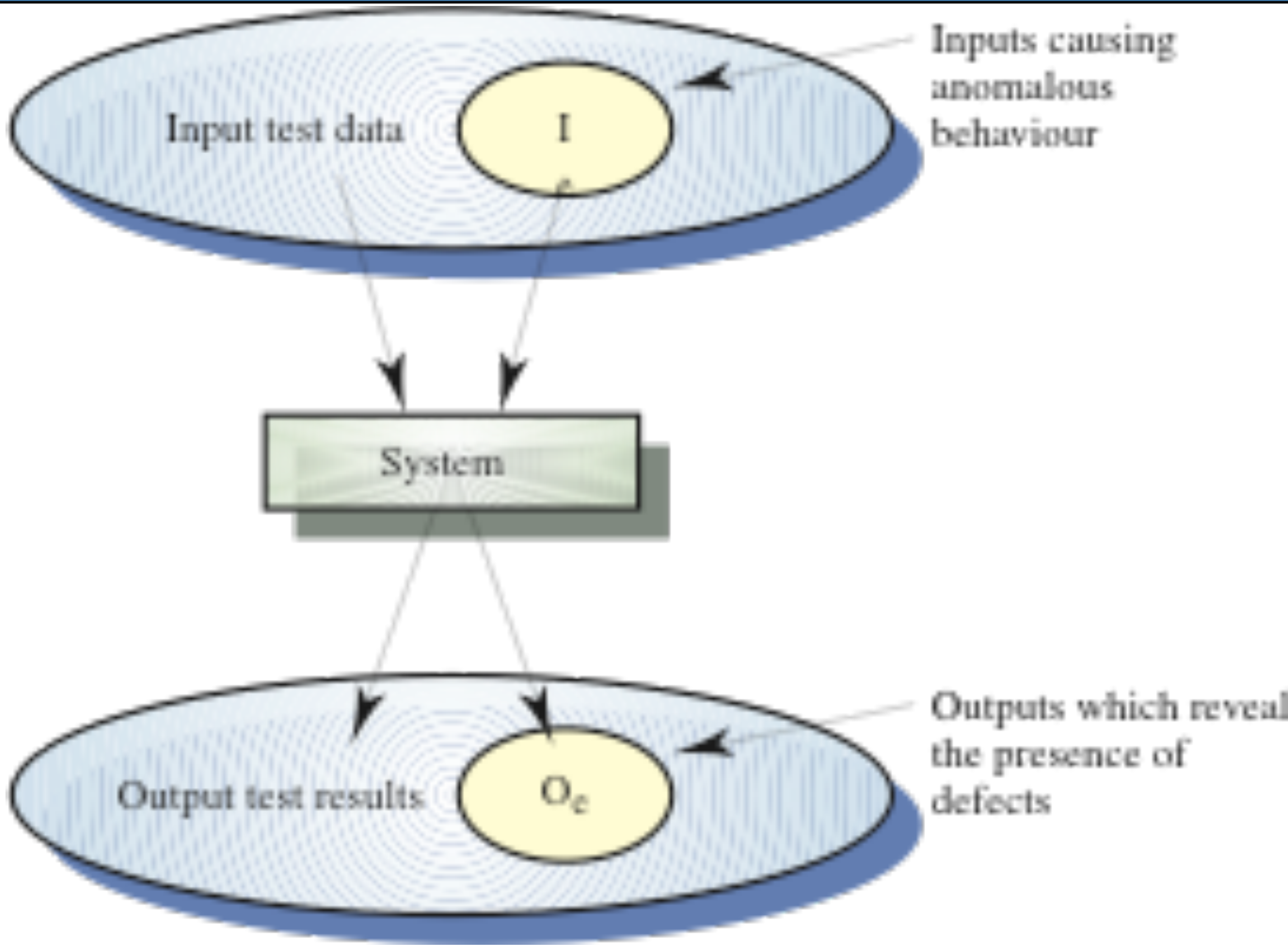
- **Black-box (or functional) testing**: Testing techniques that use the specification as the point of reference for test selection and adequacy.
  - a.k.a specification-based testing, functional testing

Which approach is superior?

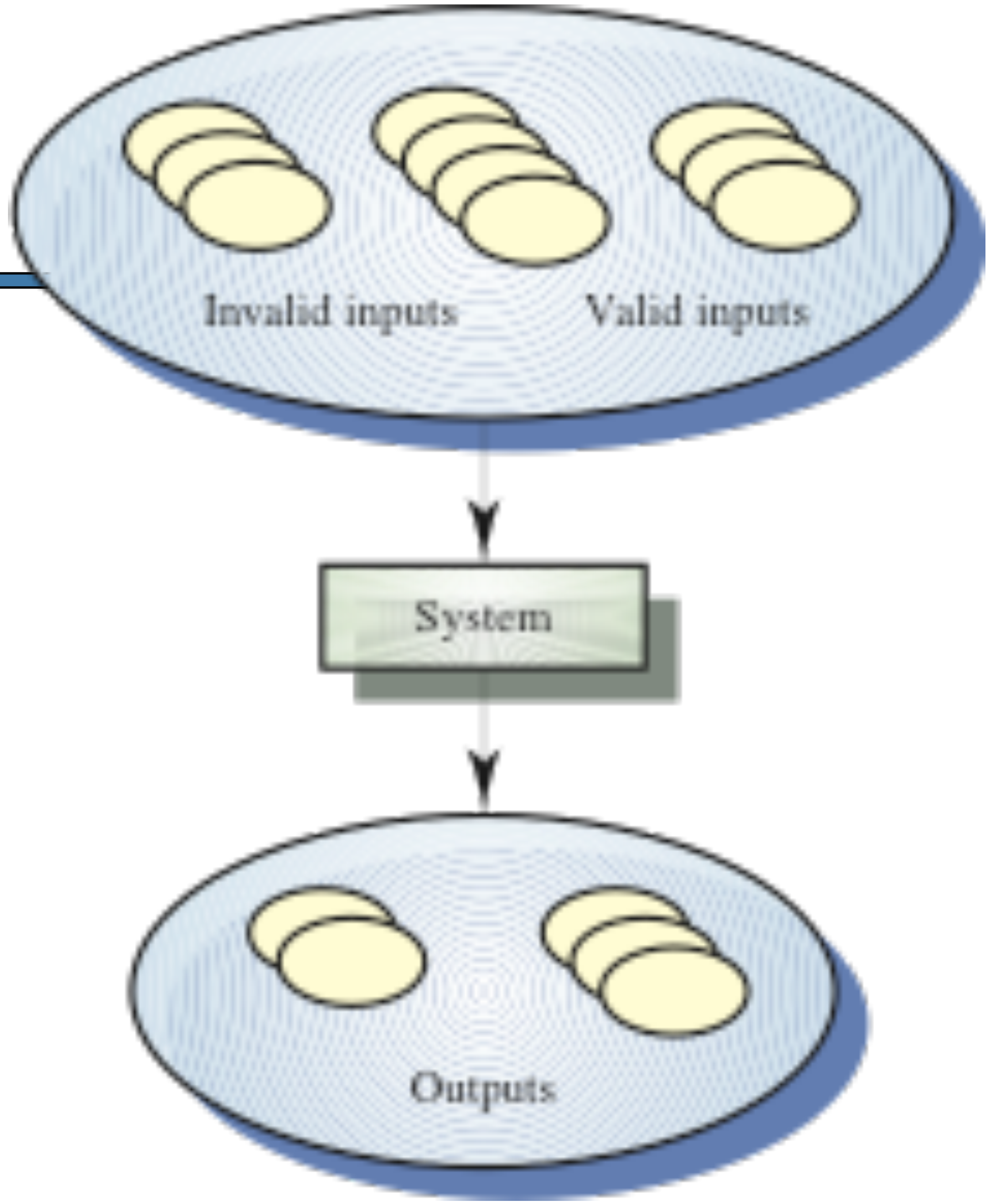
Black-box Testing

- Characteristics of Black-box testing:
  - Program is treated as a black box.
  - Implementation details do not matter.
  - Requires an end-user perspective.
  - Criteria are not precise.
  - Test planning can begin early.

Black-box Testing



Equivalence Partitioning



Search Routine Specification

procedure Search (Key : INTEGER ; T: array 1..N of INTEGER;
Found : BOOLEAN; L: 1..N) ;

Pre-condition
-- the array has at least one element
1 <= N

Post-condition
-- the element is found and is referenced by L
(Found and T (L) = Key)
or
-- the element is not in the array
(**not** Found **and**
not (**exists** i, 1 <= i <= N, T (i) = Key))

Search Routine - Input Partitions

- Inputs which conform to the pre-conditions.
- Inputs where a pre-condition does not hold.
- Inputs where the key element is a member of the array.
- Inputs where the key element is not a member of the array.

Search Routine - Input Partitions

Array	**Element**
Single value	In array
Single value	Not in array
More than 1 value	First element in array
More than 1 value	Last element in array
More than 1 value	Middle element in array
More than 1 value	Not in array

Search Routine - Test Cases

Input array (T)	**Key** (Key)	**Output** (Found, L)
17	17	true, 1
17	0	false, ??
17, 29, 21, 23	17	true, 1
41, 18, 9, 31, 30, 16, 45	45	true, 6
17, 18, 21, 23, 29, 41, 38	23	true, 4
21, 23, 29, 33, 38	25	false, ??

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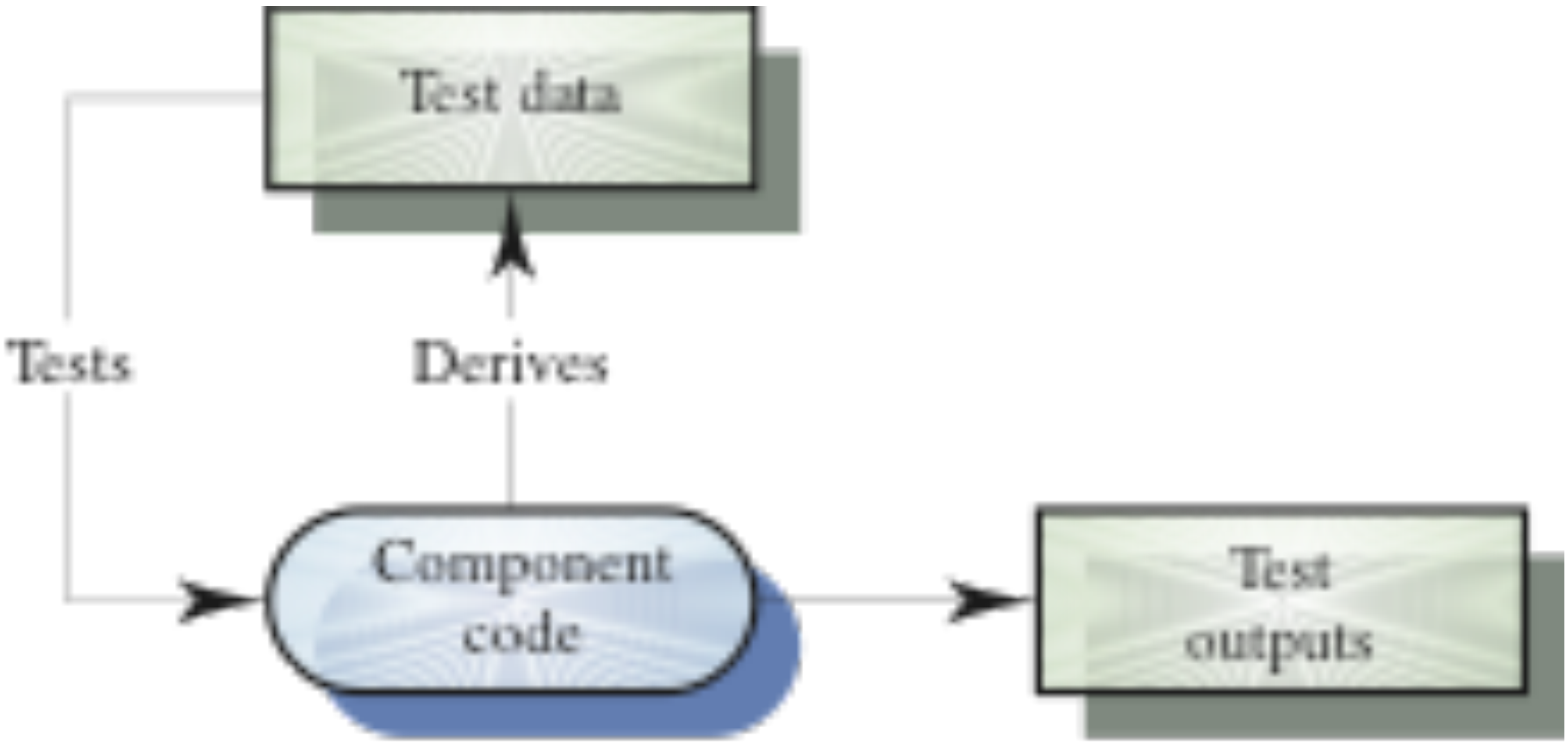
White-box Testing

- Characteristics of white-box testing:
  - Looks at implementation details.
  - Aims at exercising the different control and data structures used in the program.
  - Requires the programmer's knowledge of the source code.
  - Criteria are quite precise as they are based on program structures.
  - Assumes that the source code fully implements the specification.

White-box Testing



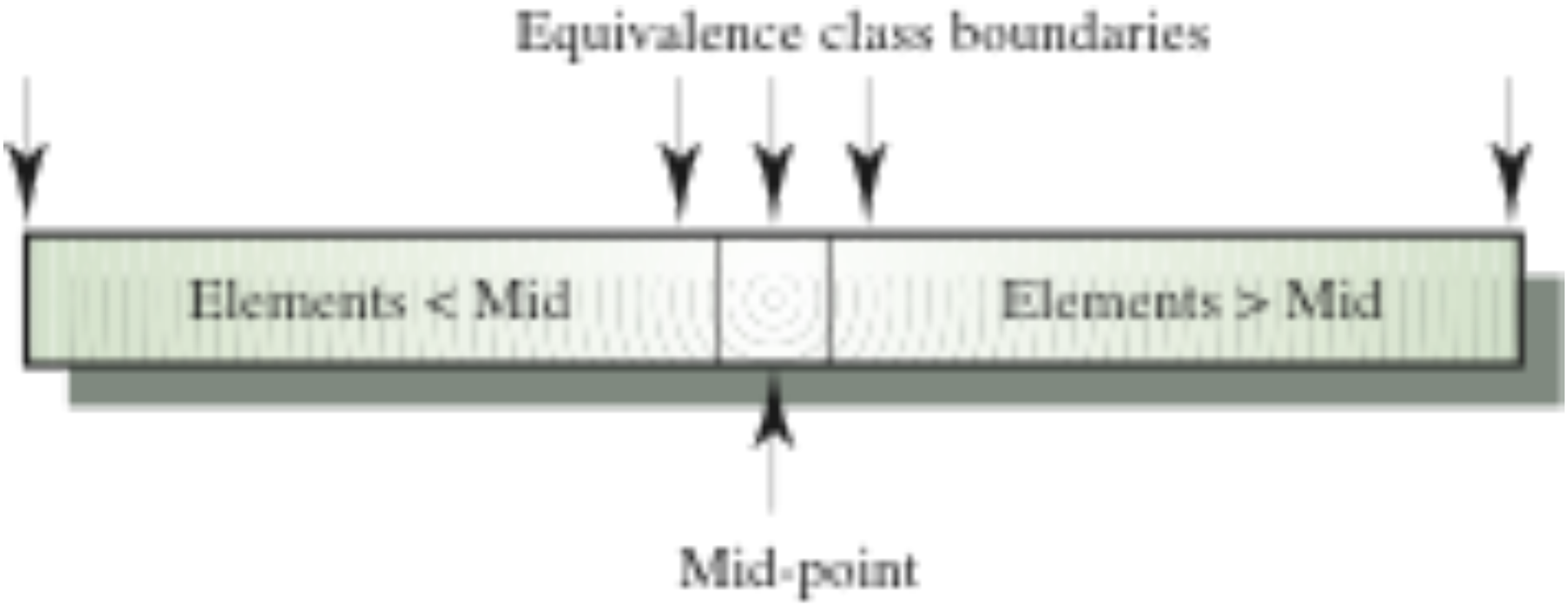
```
class BinSearch {

// This is an encapsulation of a binary search function that takes an array of
// ordered objects and a key and returns an object with 2 attributes namely
// index - the value of the array index
// found - a boolean indicating whether or not the key is in the array
// An object is returned because it is not possible in Java to pass basic types by
// reference to a function and so return two values
// the key is -1 if the element is not found

	public static void search ( int key, int [] elemArray, Result r )
	{
		int bottom = 0 ;
		int top = elemArray.length - 1 ;
		int mid ;
		r.found = false ; r.index = -1 ;
		while ( bottom <= top )
		{
			mid = (top + bottom) / 2 ;
			if (elemArray [mid] == key)
			{
				r.index = mid ;
				r.found = true ;
				return ;
			} // if part
			else
			{
				if (elemArray [mid] < key)
					bottom = mid + 1 ;
				else
					top = mid - 1 ;
			}
		} //while loop
	} // search
} //BinSearch
```

Binary search (Java)

Binary Search - Equivalence Partitions

- Pre-conditions satisfied, key element in array.
- Pre-conditions satisfied, key element not in array.
- Pre-conditions unsatisfied, key element in array.
- Pre-conditions unsatisfied, key element not in array.
- Input array has a single value.
- Input array has an even number of values.
- Input array has an odd number of values.

Binary Search Equivalence Partitions



Binary Search - Test Cases

Input array (T)	**Key** (Key)	**Output** (Found, L)
17	17	true, 1
17	0	false, ??
17, 21, 23, 29	17	true, 1
9, 16, 18, 30, 31, 41, 45	45	true, 7
17, 18, 21, 23, 29, 38, 41	23	true, 4
17, 18, 21, 23, 29, 33, 38	21	true, 3
12, 18, 21, 23, 32	23	true, 4
21, 23, 29, 33, 38	25	false, ??

White-box vs. Black-box Testing

- The real difference between white-box and black-box testing is how test cases are generated and how adequacy is determined.
- In both cases, usually, the correctness of the program being tested is done via specifications.
- Neither can be exhaustive.
- Each techniques has its strengths and weaknesses.
- Should use both. In what order?

Is Complete Testing Possible?

- **NO.** Complete testing is both practically and theoretically impossible for non-trivial software.

Complete Functional Testing

- A complete functional test would consist of subjecting a program to all possible input streams.
- Even if the program has an input stream of 10 characters, it would require 2^{80} tests.
- At 1 microsecond/test, exhaustive functional testing would require more time than twice the current estimated age of the universe!

Complete Structural Testing

- One should design enough tests to ensure that every path is executed at least once.
- What if the loops never terminate?
- Even if loops terminate, the number of paths may be too large.

Small Versus Large Systems

- For small systems with one user, quality assurance may not be a major concern.
- As systems scale up in size and number of users, quality assurance becomes more of a concern.
- As systems dramatically scale up in size (*e.g.*, millions of lines of code), our quality criteria may have to change as exhaustive testing may not be economically possible.
  - *E.g.*, a 75% code coverage may be acceptable.

How About Correctness Proofs?

- Requirements are specified in a formal language.
- Each program statement is used in a step of an inductive proof.
- In practice, such proofs are time consuming and expensive.
- Proving the consistency and completeness of a specification is a provably unsolvable problem, in general.
- Proofs may have bugs.

Testing Strategy

- Divide-and-conquer !
- We begin by ‘testing-in-the-small’ and move toward ‘testing-in-the-large’
- For conventional software
  - The module (component) is our initial focus
  - Integration of modules follows
- For OO software
  - our focus when ‘testing in the small’ changes from an individual module (the conventional view) to an OO class that encompasses attributes and operations and implies communication and collaboration

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Testing Strategy

- Understand / formulate quality objectives
- Identify the appropriate testing phases for the given release, and the types of testing the need to be performed.
- Prioritize the testing activities.
- Plan how to deal with “cycles”.

Testing Phases

- Unit Testing
- Integration Testing
- System Testing
- Alpha Testing
- Beta Testing
- Acceptance Testing

System Testing

- Performed by a separate group within the organization.
- *Scope*: Pretend *we* are the end-users of the product.
- Focus is on functionality, but must also perform many other types of tests (e.g., recovery, performance).
- Black-box form of testing.
- Test case specification driven by use-cases.

System Testing

- The whole effort has to be planned (System Test Plan).
- Test cases have to be designed, documented, and reviewed.
- Adequacy based on requirements coverage.
  - but must think beyond stated requirements
- Support tools have to be [developed]/used for preparing data, executing the test cases, analyzing the results.

System Testing

- Group members must develop expertise on specific system features / capabilities.
- Often, need to collect and analyze project quality data.
- The burden of proof is always on the ST group.
- Often, the ST group gets the *initial blame* for "not seeing the problem before the customer did".

Other Testing Phases

- Depending on the system being developed, and the organization developing the system, other testing phases may be appropriate:
  - Alpha / Beta Testing
  - Acceptance Testing

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Types of Testing

- Functionality
- Recovery
  - Force the software to fail in a variety of ways and verify that recovery is properly performed.
- Performance
  - Test the run-time performance of the software.
- Stress
  - Execute a system in a manner that demands resources in abnormal quantity, frequency, or volume.

Types of Testing

- Security
  - Verify that protection mechanisms built into a system will, in fact, protect it from improper penetration
- Reliability
  - Operate the system for long periods of time and estimate the likelihood that the the requirements for failure rates, mean-time-between-failures, and so on, will be satisfied.
- Usability
  - Attempt to identify discrepancies between the user interfaces of a product and the human engineering requirements of its potential users.

…

Regression Testing

- The activity of re-testing modified software.
- It is common to introduce problems when modifying existing code to either correct an existing problem or otherwise enhance the program.
- Options:
  - Retest-none (of the test cases)
  - Retest-all
  - Selective retesting
- For some systems, regression testing can be fairly expensive.