CS314, Colorado State University
Software Engineering
Notes 3:
Verification & Validation
(V & V)

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## Software Failures

- IRS Automated Income Tax Form Processing System (Sperry 1980's).
- SDI Star Wars software.
- Ariane-5 Rocket.
- Therac-25 Accidents.
- Year-2000 bug.
- London Ambulance Service Fiasco.
- Colorado Benefits Management System (2004).
- MS Zune failure on December 31, 2008.
- ASCSU Course Survey failures (2011 - ?).
- Affordable Care Rollout.

...




## Focus: Evaluating Software Quality

- Verification and validation (V & V) techniques and terminology.
- Testing theory.
- Functional (Black box) and structural (white box) testing.
- Test plans.
- Inspections.

All tied to testing object-oriented software.




## Validation

- Validation refers to checking to make sure that we are building what the customer wants.
- We ask:

*"Did we build the right thing?"*




## Verification

- Verification refers to checking to see if we have built the software so that it matches some specification.
- We ask:

*"Did we build the thing right?"*




## Testing

- Run the program on sample inputs.
- Check the correctness of the output.
- Test run success is evidence of correctness.
- Testing is part of either verification or validation, or both (V & V).

## V & V Is Not Just Applied to Code

- V & V techniques can be applied to non-running software documents.
  - Requirements specifications.
  - Designs.
  - Test plans.
  - Documentation.



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## V & V Techniques

- Static analysis: we do not run anything.
- Formal verification: mathematical proofs.
- Dynamic analysis: usually testing.
- Inspections: semi-formal study of a software document (really, a form of static analysis).



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## V & V Terminology

- Software Fault: a static defect in the software.
- Software error: an incorrect internal state caused by a fault at runtime.
- Software Failure: external, observable incorrect program behavior with respect to the explicit or expected requirements.

Source: Ammann and Offutt, *Introduction to Software* Testing, Cambridge University Press, 2008.



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## V & V Terminology

- Testing: evaluating software by observing its execution.
- Failure: execution that results in a failure.
- Debugging: the process of finding a fault given a failure.



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## Testing Terminology

- Unit testing: testing a program unit: individual procedures, functions, methods, or classes.
- Integration testing: testing connection between units and components.
- System testing: test entire system.
- Acceptance testing: testing to decide whether to purchase the software.



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## A High-Level View of Testing Object-oriented Systems

- System tests: may be developed from
  - User stories.
  - Use Cases*.
  - System Sequence Diagrams*

  *More on these UML diagrams later.
- Integration tests:
  - Use cases and system sequence diagrams.
  - Subsystem sequence diagrams.
- Unit tests:
  - Packages of classes.
  - Method combinations.
  - Individual methods.



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## Testing Terminology (2)

- Alpha testing: system testing by a user group within the developing organization.
- Beta testing: system testing by select customers.
- Regression testing: retesting after a software modification.

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## Dynamic Fault Classification

- Logic faults: omission or commission.
- Overload: data fields are too small.
- Timing: events are not synchronized.
- Performance: response is too slow.
- Environment: error caused by a change in the external environment.

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## Who Should Conduct Testing?

- Should the developer do the testing?
- Should we use an independent testing team?
- How is it done in industry?

 3-15

## Test Scaffolding or Test Harness

Allows us to test incomplete systems.

- Test drivers/harnesses: test components.
- Stubs: test a system when some components it uses are not yet implemented.

  Often a short, dummy program --- a method with an empty body.

 3-16

## Test Oracles

- Determine whether a test run completed with or without errors.
- Often a person, who monitors output.
  - Not a reliable or efficient method.
- Automatic oracles check output using another program.
  - Requires some kind of executable specification.
  - Asserts in JUnit.

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## Testing Theory: Why Is Testing So Difficult?

- Theory often tells us what we can't do.
- Testing theory main result: *perfect testing* is impossible.

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## An Abstract View of Testing

- Let program *P* be a function with an input domain *D* (i.e., the set of all ints).
- We seek test data *T*, which will include selected inputs of type *D*.
  - *T* is a subset of *D*.
  - *T* must be of finite size.

  Why?

 3-19

## We Need a Test Oracle

- Assume the best possible oracle --- the specification *S,* which is function with input domain *D.*
- On a single test input *i*, our program passes the test when

  *P(i) = S(i)*

 3-20

## For Perfect Testing

1. If all of our tests pass, then the program is correct.
   - All of our tests t in test set T, P(t) = S(t), then we can be sure that the program will work correctly for all elements in D.
   - If any tests fail we look for a fault.
2. We can tell whether the program will eventually halt and give a result for any t in our test set T.

 3-21

## But, Both Requirements Are Impossible to Satisfy.

- 1st requirement can be satisfied only if *T= D.*

  We test all elements of the input domain.
- 2nd requirement depends on a solution to the *halting problem*, which has no solution.

  An *undecidable* problem.

  ?

 3-22

## Undecidable Problem

A decision **problem** for which it is known to be impossible to construct a single algorithm that always leads to a correct yes-or-no answer. A decision **problem** is any arbitrary yes-or-no question on an infinite set of inputs [Wikipedia].

 3-23

## Other Undecidable Testing Problems

- Is a control path feasible?

  Can I find data to execute a program control path?
- Is some specified code reachable by any input data?

These questions cannot, *in general*, be answered.

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## Software Testing Limitations

- There is no perfect software testing.
- Testing can show defects, but can never show correctness.

We may never find all of the program errors during testing.

There is always one more "bug".

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## A Pragmatic Testing Strategy

- Divide domain *D* into sub-domains *D1, D2, ..., Dn*, which represents some aspect of the program.
- Select at least one test case from each *Di*.

We cannot test each sub-domain perfectly, but we can do better on a piece of the functionality.

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## Software Faults, Errors & Failures

- Software Fault : A static defect in the software
- Software Error : An incorrect internal state that is the manifestation of some fault
- Software Failure : External, incorrect behavior with respect to the requirements or other description of the expected behavior

**Faults in software are design mistakes and will always exist**

 3-27

## Fault & Failure Model (RIP Model)

Three conditions necessary for a failure to be observed

1. Reachability : The location or locations in the program that contain the fault must be reached.
2. Infection : The state of the program must be incorrect.
3. Propagation : The infected state must propagate to cause some output of the program to be incorrect.

 3-28

## Black-Box Class Testing

- Black-Box testing: test a "component" taking an external view.
  - Use the specification to derive test cases.
  - No access to source code.
- Black-Box class testing.
  - Generate tests by analyzing the class interface.
  - Don't look at method bodies.

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## Black-Box Class Testing (2)

- Look at the class in isolation, and in conjunction with other associated classes.
- Test each class method, and test sequences of messages that class objects should respond to.
- May need stubs and/or test drivers.

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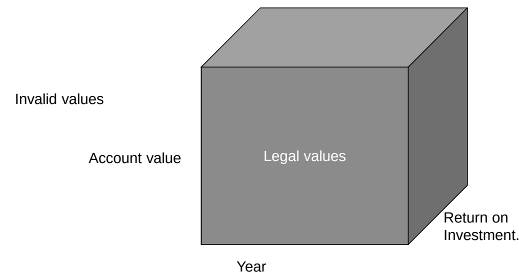
## Black-Box Class Testing (3)

- Group class objects into categories.
- Test each method for each category.
- A *test plan* documents all of the tests to be performed.



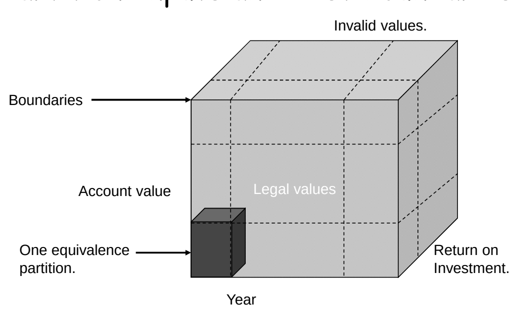

## An Infinite Number of Possible Inputs, But a Finite Number of Tests







## Partition Inputs and Test Boundaries







## Determining Equivalence Partitions

- Find an ordering of the class objects.
- Example: Finding Java String objects to test.
  - Canonical ordering of string objects:
    - "", "a", "b", ..., "aa", "ab", ..., "zz...zz"
- Use the ordering to select test objects.




## Use the Ordering to Select Test Cases

Find objects at extremes and next to extremes:
- Minimum size: "", "a"
  - Long strings: "zz...zz", "zz...zy"
- Middle length Strings.
- Different types of Strings:
  - numbers
  - control characters: "^D^C"
  - symbols: "&$@+->“
- Invalid strings: a null String variable. For C++, you can set a String variable to an integer.




## Ex: Testing Java Class *Stack*

Stack method interface:
- boolean empty()
- Object peek()
- Object pop()
- void push(Object element)
- int search(Object element)
  - ***Boo Hiss!!*** This is non-stack type of operation.
- Object Stack(): The default constructor.

## Classify the Operations

- Constructors/Destructors:
  - Stack()
  - ~Stack() in C++
- State changing operations:
  - pop()
  - push(Object e)
- Non-state changing operations:
  - empty()
  - peek()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## Test Each Type of Operation

- Constructors: test each constructor with all orderings of parameter boundary values.
- Destructors: test with each constructor.
- State changing operations: try to change the object state from every "state" to every other "state".
- Non-state changing operations: test on stacks in each "state".


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## "State"

- Really a group of related states.
- Example stack states:
  - Empty stacks,
  - Mid-size stacks,
  - Just under the maximum size stack,
  - Large or full stacks.
  - Empty stacks,
  - Mid-size stacks,
  - Just under the maximum size stacks.


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## Testing *Multiplicity*

- Create several stacks and test, alternating between them.
- This will determine whether each stack object has an independent state (independent instance variables).


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## The Test Oracle

- How do you know if an item is successfully pushed onto a stack?
- Examine the behavior of the resulting stack after the push operation is performed.


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## Class Testing Plan Structure

- Class name.
- For each public method:
  - Method name.
  - For each test case for the method:
    - A test ID.
    - Test strategy: black-box (BB), white-box (WB), or other; test of valid or invalid input?
    - Test description.
    - Verification: what are the expected outputs? How do you identify success or failure?


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## Class Stack BB Test Plan

Constructor method Stack() tests:

- Test: Stack.Stack1
  - Strategy: Black Box, Valid.
  - Description: Create a Stack.
  - Verification: A stack object is created; a non-null Stack reference is returned.
- Test: Stack.Stack2
  - Strategy: Black Box, Valid .
  - Description: Create many Stacks.
  - Verification: Many stack objects are created; non-null, not equal Stack references are returned.




## Class Stack BB Test Plan (2)

Method push(Object e) tests:

- Test: Stack.push1
  - Strategy: Black Box, Valid
  - Description: Push one item onto a Stack.
  - Verification: The item is on the top of the stack and can be popped off.
- Test: Stack.push2
  - Strategy: Black Box, Valid
  - Description: Push many items onto a Stack.
  - Verification: The items can be popped off in reverse order.




## Class Stack BB Test Plan (3)

Method push(Object e) tests:

- Test: Stack.push3
  - Strategy: Black Box, Valid
  - Description: Push many items onto a Stack.
  - Verification: The correct items can be popped off each stack in reverse order.
- Test: Stack.push4
  - Strategy: Black Box, Valid
  - Description: Push a null item onto a Stack.
  - Verification: The null object can be popped off.




## Class Stack BB Test Plan (4)

Method push(Object e) tests:

- Test: Stack.push5
  - Strategy: Black Box, Invalid
  - Description: Push an items onto a null Stack.
  - Verification: An exception is raised.
- Test: Stack.push6
  - Strategy: Black Box, Invalid
  - Description: Push a null item onto a non-Stack object.
  - Verification: It won't compile in Java; An exception is raised in C++.




## Class Stack BB Test Plan (5)

Method pop() tests:

- Test: Stack.pop1
  - Strategy: Black Box, Valid
  - Description: Pop 1 item from a Stack.
  - Verification: The item can be popped off.
- Test: Stack.pop2
  - Strategy: Black Box, Valid
  - Description: Pop many items from a Stack.
  - Verification: The items can be popped off.




## Class Stack BB Test Plan (6)

Method pop() tests:

- Test: Stack.pop3
  - Strategy: Black Box, Valid
  - Description: Pop many items from a Stack.
  - Verification: The item can be popped off in reverse order.
- Test: Stack.pop4
  - Strategy: Black Box, Valid
  - Description: Pop a null item from a Stack.
  - Verification: The item can be popped off.

## Class Stack BB Test Plan (7)

Method pop() tests:

- Test: Stack.pop5
  - Strategy: Black Box, Invalid
  - Description: Pop a null Stack.
  - Verification: An exception is raised.
- Test: Stack.pop6
  - Strategy: Black Box, Invalid
  - Description: Pop a non-Stack object.
  - Verification: Will not compile in Java; raises an exception in C++


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## Class Stack BB Test Plan (8)

Method pop() tests:

- Test: Stack.pop7
  - Strategy: Black Box, Invalid
  - Description: Pop an empty Stack.
  - Verification: An exception is raised.

Method empty() tests:

- Test: Stack.empty1
  - Strategy: Black Box Valid
  - Description: Test a newly created Stack.
  - Verification: Returns true.


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## Class Stack BB Test Plan (9)

Method empty() tests:

- Test: Stack.empty2
  - Strategy: Black Box Valid
  - Description: Test a Stack with a history of 1 push and 1 pop.
  - Verification: Returns true.
- Test: Stack.empty3
  - Strategy: Black Box, Valid.
  - Description: Test a Stack with many pushes, and an equal number of pops.
  - Verification: Returns true.


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## Class Stack BB Test Plan (10)

Method empty() tests:

- Test: Stack.empty4
  - Strategy: Black Box Valid
  - Description: Test after a push-pop-push-pop sequence.
  - Verification: Returns true.
- Test: Stack.empty5
  - Strategy: Black Box, Valid.
  - Description: Test after 1 push.
  - Verification: Returns false.


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## Class Stack BB Test Plan (11)

Method empty() tests:

- Test: Stack.empty6
  - Strategy: Black Box Valid
  - Description: Test after many pushes.
  - Verification: Returns false.
- Test: Stack.empty7
  - Strategy: Black Box, Invalid.
  - Description: Test a null Stack.
  - Verification: Exception.


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## Class Stack BB Test Plan (12)

Method empty() tests:

- Test: Stack.empty8
  - Strategy: Black Box Invalid
  - Description: Test a non-Stack.
  - Verification: Won't compile in Java. Exception in C++.


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## Test Drivers/Harnesses

- Must be able to:
  - Build the test cases.
  - Log testing results.
  - Make success or failure observable.
- Can be
  - Hard-coded.
  - Reads tests from a file.
  - Interactive.
  - Built using a tool like Junit.
- Each test should run independently.

 3-55

## Example Class Test Driver

Handcrafted test driver:
- No use of JUnit or similar tool.
- Not recommended. For demonstration purposes.

```
public class StackTest {
    public static void main (String[] args)
                        throws IOException{
        /** We run the tests **/
        push1();
        push7(); /* exception handler prevents crash */
        push2();
        push3();
        push5();
}
```

Note: push7 is an invalid test – pop an empty stack.

 3-56

## Black box testing example

Program specification:
- The program receives an invoice as input (invoice structure is excluded here).
- The invoice must be inserted into an invoice file that is sorted by date.
  - It must be inserted in the appropriate position: If other invoices exist in the file with the same date, then the invoice should be inserted after the last one.
  - Consistency checks must be performed: the program should verify whether the customer is already in a corresponding file of customers, whether the customer's data in the two files match, …

Test set
- Invoice whose date is the current date
- Invoice whose date is before the current date
  - Invoice whose date is the same as that of some existing invoice
  - Invoice whose date does not exist in invoice file
- Incorrect invoices that can be used to check different types of inconsistencies

 3-57

## Testing boundary conditions

- Some programming errors are on the boundary of input domains/partitions used for testing.

```
if x > y then
      do something;
else
      do something else
end if;
```

- Input domains
  - D1:{x>y}
  - D2:{x <= y}

  Easy to miss the case x=y when selecting from D2.
- Rule of thumb: test using values at the boundaries of the input domains.

 3-58

## Structural Testing (White Box Testing)

- Look at the internal program structure.
- Tests selected to cause all "parts" of a program to run.
  - Each "part" represents a *test requirement.*
  - We want to test each requirement.
- Can detect faults in implementation structure that are not represented in any external specification.

 3-59

## Example: String Reversal Program Error.

Algorithm:
1. Divide input string into fixed-sized pages.
2. Push each page onto a stack.
3. Pop the characters out in reverse order.

 3-60

## Black Box Tests

- Vary string lengths:
  - Empty strings,
  - Short strings,
  - Long strings,
  - Medium length strings.
- All might pass the tests.




## Hidden Bug (Fault)

- The programmer assumed that the last page is partially full.
  The program appends a "null'' termination character, only when the last page is partially full.
- If the input string is an exact multiple of the page size, there is no partial page.
- The termination character ends execution.
  Without it the program fails.




## Failures Occur "Rarely"

- Assume that the page length is 100 characters.
  1% chance that black-box testing, will reveal the fault.
- The specs do not mention the termination character.
- White-box testing must cover code branches dealing with the termination character.
  Tests must include a case where the termination character is not appended.




## Structural (White Box) Test Coverage Criteria.

- Statement or node coverage.
- Branch coverage, edge coverage, or decision coverage.
- Condition coverage.
- Definition/Use (DU) Pair coverages.

...




## Test Coverage Strength (subsumption)

- Branch coverage is stronger than statement coverage (BC subsumes SC),
- Condition coverage is stronger than branch coverage (CC subsumes SC), and
- Definition/Use coverage is stronger than branch coverage (DU subsumes CC).

If tests satisfy a coverage criteria, they also satisfy all weaker ones.

(but sometimes tests that satisfy a weaker criteria find bugs missed by tests that satisfy a stronger criteria.)




## Example

- Look at the code:
  if (A) S1;
  S2;
- We can cover both S1 and S2 with 1 test.
  Just set A=true.
- To cover all branches, we must also test the path that skips S1.
  We need another test case where A=false.

## Sometimes Stronger Coverage is Needed

- Buggy code:
  i = 0;
  if (A) i = 1;
  x = y/i;

- No error when you test with A=true.
- Bombs if you test with A=false.

Branch coverage reveals the error, but statement coverage may not!

 3-67

## An Error, Not Detected by Branch Coverage

```
/* Assume boolean F1, F2 are
   declared & assigned values
*/
...
 if (A() && B()) x = y + z;
 ...

 boolean A() {
  if (F1) {
    q = 0;
    return true;
  }
  else return false;
 }

...

 boolean B() {
  if (F2) {
    q = 0;
    return true;
  }
  else {
    x = 10/q;
    return false;
  }
 }
```

 3-68

## We Test the Code

- Branch coverage is satisfied with 2 tests:
  - F1==true and F2==true: takes the true path.
  - F1==false and F2==false: takes the false path.
- The failure occurs when F1==true & F2==false.
- Condition coverage or DU pairs coverage would require this test.

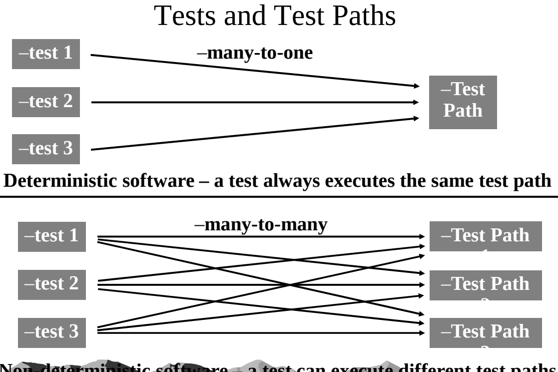
 3-69

## Tests and Test Paths

- path (*t*) : The test path executed by test *t*
- path (*T*) : The set of test paths executed by the set of tests *T*
- Each test executes one and only one test path
- A location in a graph (node or edge) can be reached from another location if there is a sequence of edges from the first location to the second
  - *Syntactic reach* : A subpath exists in the graph
  - *Semantic reach* : A test exists that can execute that subpath

 3-70

## Tests and Test Paths




 3-71

## Definitions & Uses

- Definition: the point in a program where a variable's value is set or changed.
- Use: the point where a variable's value is used.
- DU-path: a program path from a variable definition to a use, without an intervening definition to the variable.

 3-72

## Definition/Use (DU) Pair Coverage
## The All-Uses Coverage Criterion

- For each variable definition:
  Test a def-free path to each reachable use of the definition.
  (Test one DU path for each DU-pair for each variable.)
- In prior example: we would need include a DU path from
  definition "q = 0;" to the use "x = 10/q;"




## Another Example Program

```
while (notDone) do {
 if (A) x = f(x);
 else   x = g(x);
 ...
}
```

- **then** branch:
  First references the prior value of x (a use of x) & then redefines x (a definition of x).
- **else** branch:
  Does the same thing.

Test paths required by the all-uses criterion:
- Loop through the **then** branch twice in a row.
- Loop through the **else** branch twice in a row.
- 1 cycle through the **then** branch followed by a cycle through the **else** branch.
- A cycle through the **else** branch followed by a cycle through the **then** branch.




## Testing Limitations

- If our testing results in:
  - 100% statement coverage,
  - 100% branch coverage,
  - 100% condition coverage,
  - 100% DU-pair coverage.
- The program may still have hidden faults.

Why is that true?




## White Box Testing Support Tools

- Instrument source code to report on program items that are "covered" during testing.
- Many tools exist. Search with the following search words: "java test coverage tools"
  - EMMA: statement coverage.
  - EclEmma, which is similar to Emma, but works with Eclipse.
  - CodeCover: Includes statement, branch, and condition-term coverage.




## Software Inspections

- Semi-formal evaluation of software products for V&V.
- Organized with 2 or more "inspectors".
- Objective: find errors early.




## What to Inspect

All software documents can be reviewed:
- Requirements specifications: are they complete? Are they correct?
- Designs: do they satisfy all requirements? Is the design too complex? Are there errors?
- Code: look for faults.
- Documentation: look for accuracy errors. Is it readable.
- Test plans: completeness, correctness.

## Inspections Focus on Goals

- Find and record errors.
- Don't repair them.
- Participants review software documents independently and then meet to review & report findings.
  (Meetings can be virtual).

 3-79

## Review Guidelines [Pressman]

1. Review the product, not the producer.
2. Set an agenda and maintain it.
3. Limit debate and rebuttal.
4. Enunciate problem areas.
5. Take written notes.

 3-80

## Review Guidelines [Pressman]

6. Limit the number of participants & insist on advance preparation.
7. Develop & use a review checklist.
8. Allocate resources & time schedule.
9. Conduct training for all reviewers.
10. Review your early reviews.

 3-81

## Software Documents Are Meant to Be Read by People

- Commercially successful software will be modified many times over many years by many people.
- Inspections are more effective when documents are readable.

 3-82

## Software Documents Are Meant to Be Read by People

- Documents should have a simple structure, and not be verbose.
- Comments should add to understandability & not restate the obvious.
- Avoid overly complex structures without very strong justification.  Document these complex solutions.

 3-83

## Software That Can Be Verified

- Is simply structured.
- Has a written, valid requirements specification.
- Evolved to its current form following a well-defined development process.

 3-84

## Summary

- V & V involves making sure that:
  - We built the right software (validation).
  - We built the software right (verification).
- Perfect testing is impossible.
- Testing has many facets:
  - What we test: from system testing to unit testing.
  - When we test: from alpha testing to regression testing.




## Summary

- Black box testing involves developing test cases in terms of the specification.
- White box (structural) testing involves using test cases to cover all parts of the program.
- Rigorous testing requires a comprehensive test plan.

  We saw a detailed example of a test plan for conducting black-box class testing.
- Software inspections can find faults early.