Functional Testing

Software Engineering
Andreas Zeller • Saarland University

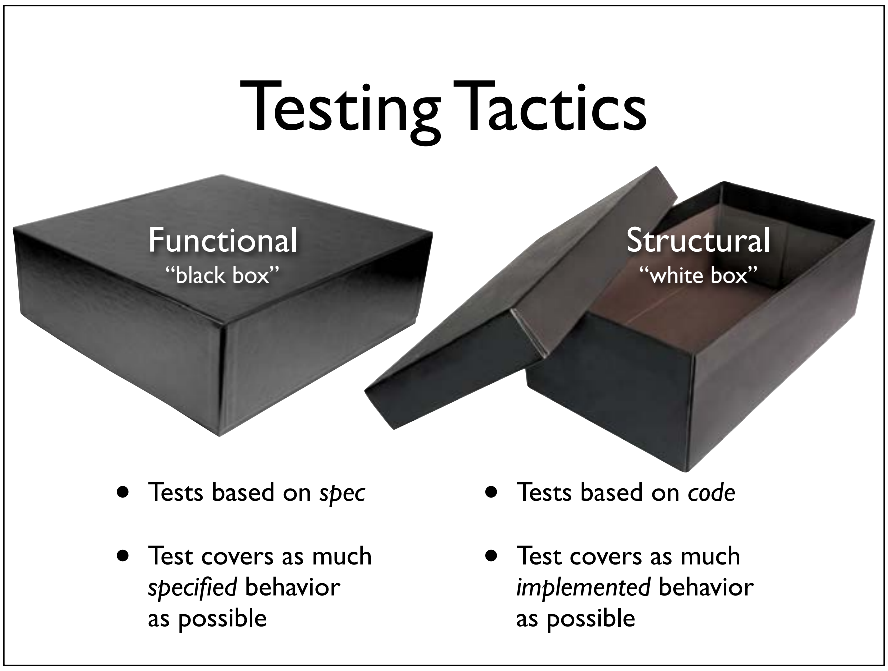
From Pressman, “Software Engineering – a practitioner’s approach”, Chapter 14 and Pezze + Young, “Software Testing and Analysis”, Chapters 10-11

Today, we’ll talk about testing – how to test software. The question is: How do we design tests? And we’ll start with functional testing.

Functional testing is also called “black-box” testing, because we see the program as a black box – that is, we ignore how it is being written

in contrast to structural or “white-box” testing, where the program is the base.

If the program is not the base, then what is? Simple: it's the specification.



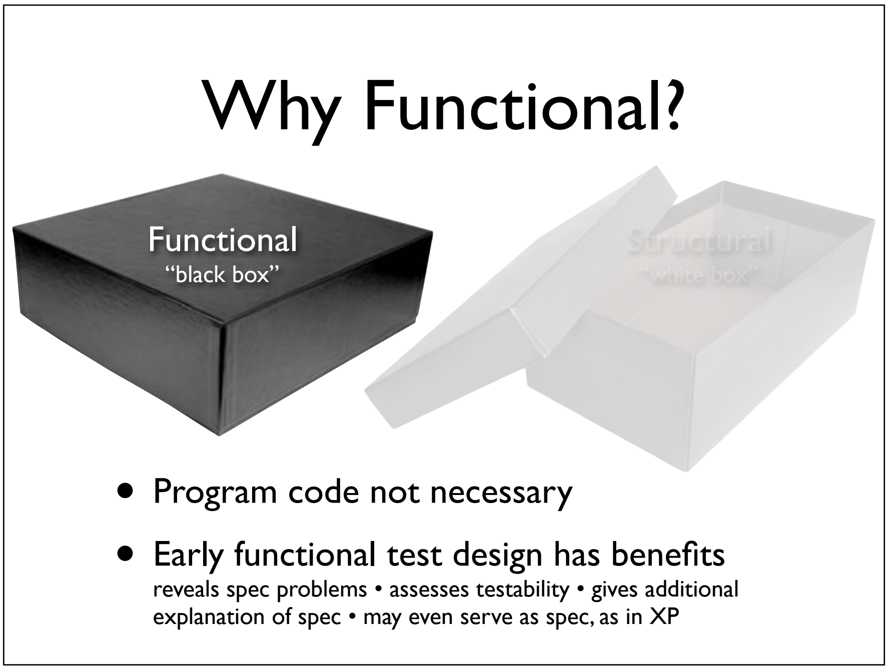
Testing Tactics

Functional
"black box"
Structural
"white box"

- Tests based on *spec*
- Test covers as much *specified* behavior as possible

- Tests based on *code*
- Test covers as much *implemented* behavior as possible

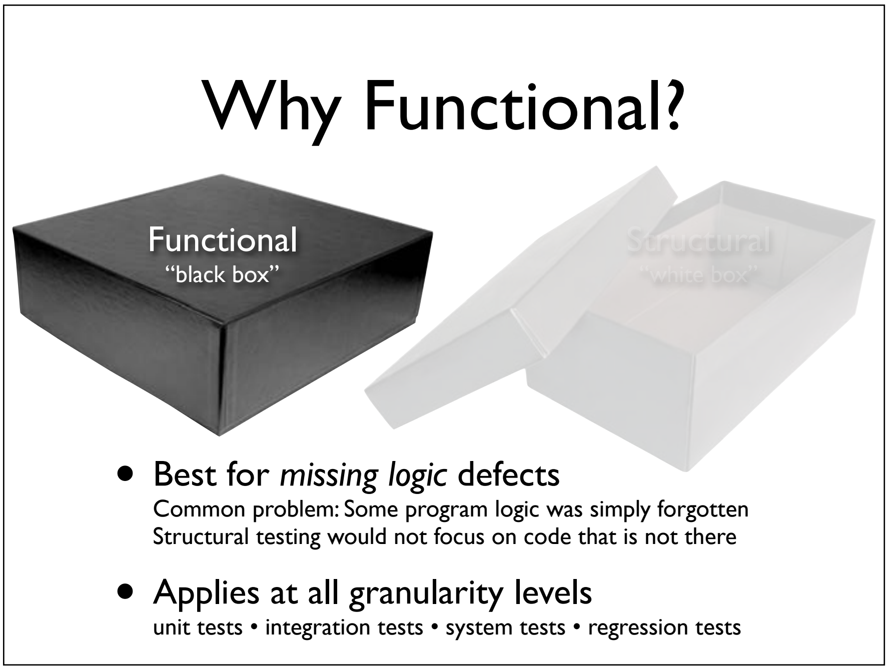
If the program is not the base, then what is? Simple: it's the *specification.*



Why Functional?

Functional
"black box"
Structural
"white box"

- Program code not necessary
- Early functional test design has benefits
  reveals spec problems • assesses testability • gives additional explanation of spec • may even serve as spec, as in XP

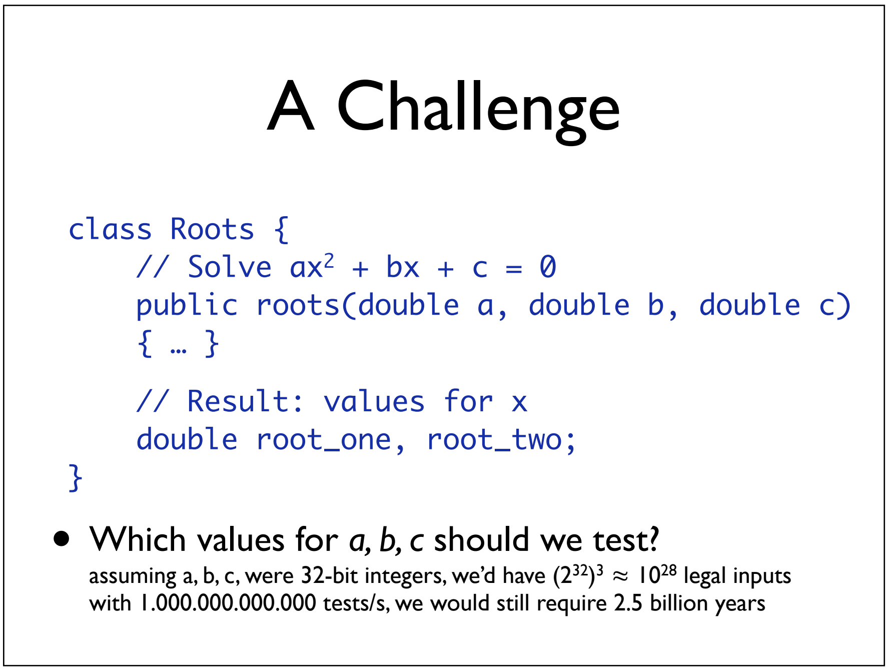


Why Functional?

Functional
“black box”
Structural
“white box”

- Best for *missing logic* defects
  Common problem: Some program logic was simply forgotten
  Structural testing would not focus on code that is not there
- Applies at all granularity levels
  unit tests • integration tests • system tests • regression tests

Structural testing can not detect that some required feature is missing in the code
Functional testing applies at all granularity levels (in contrast to structural testing, which only applies to unit and integration testing)



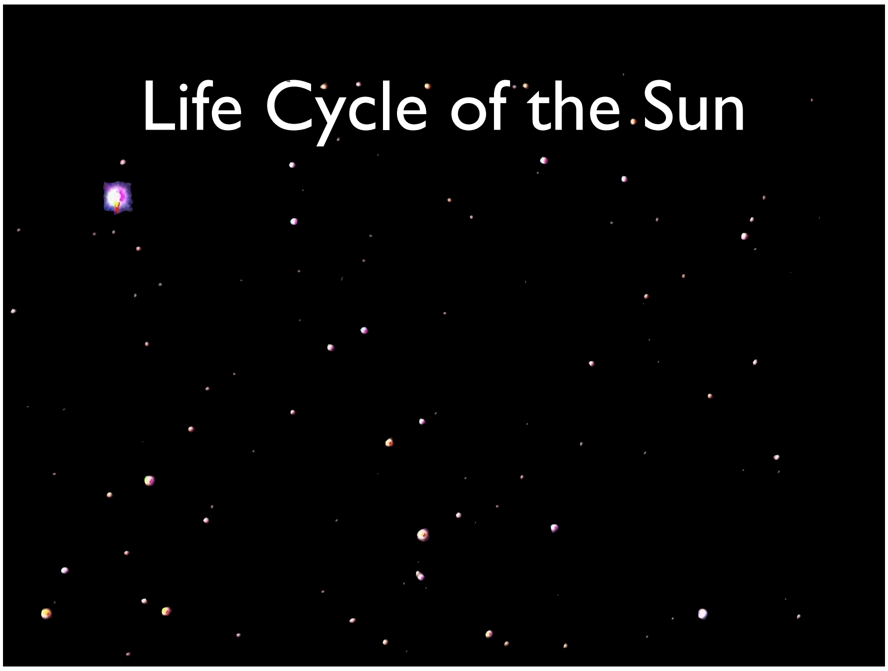
A Challenge

```
class Roots {
    // Solve ax^2 + bx + c = 0
    public roots(double a, double b, double c)
    { … }

    // Result: values for x
    double root_one, root_two;
}
```

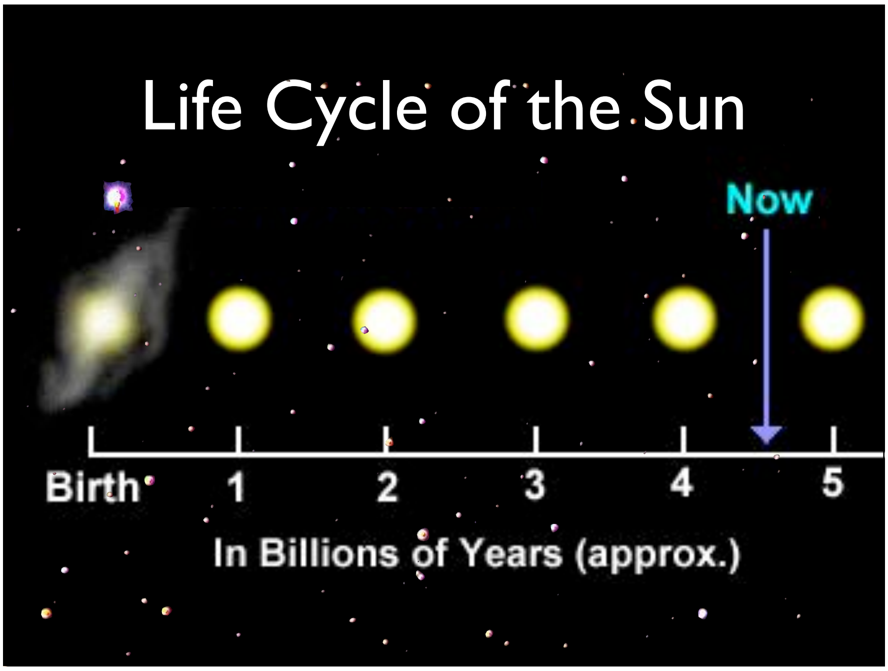
- Which values for *a, b, c* should we test?
  assuming a, b, c, were 32-bit integers, we’d have $(2^{32})^3 \approx 10^{28}$ legal inputs
  with 1.000.000.000.000 tests/s, we would still require 2.5 billion years

2,510,588,971 years, 32 days, and 20 hours to be precise.



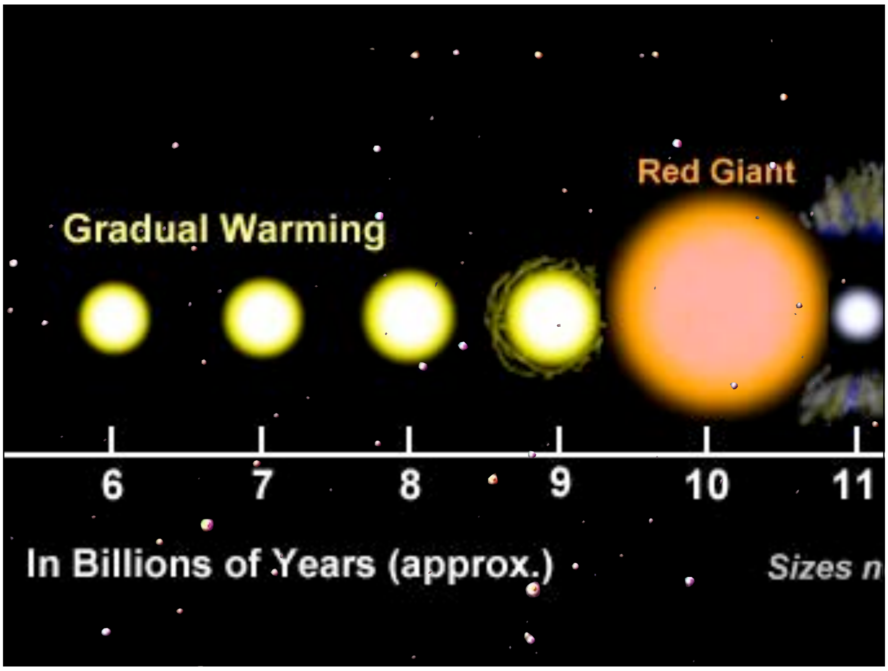
Life Cycle of the Sun

Note that in 900 million years, due to increase of the luminosity of the sun, CO2 levels will be toxic for plants; in 1.9 billion years, surface water will have evaporated (source: Wikipedia on “Earth”)

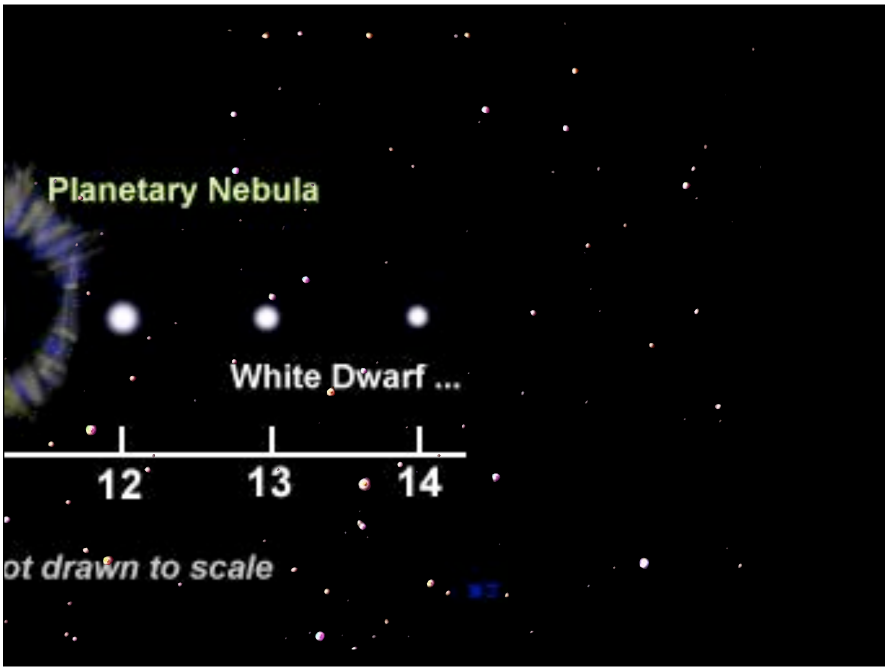


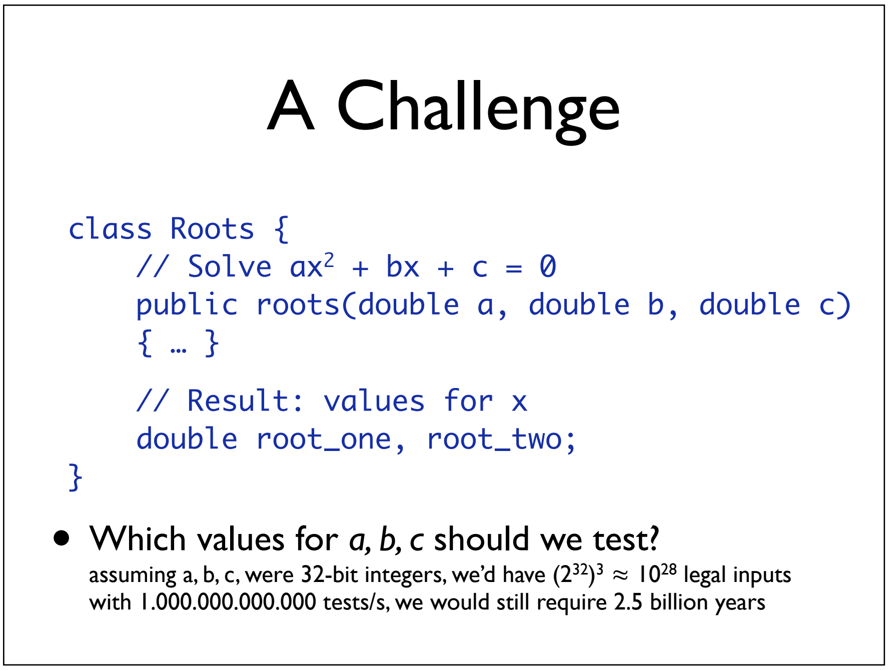
Life Cycle of the Sun

Note that in 900 million years, due to increase of the luminosity of the sun, CO2 levels will be toxic for plants; in 1.9 billion years, surface water will have evaporated (source: Wikipedia on “Earth”)



None of this is crucial for the computation, though.



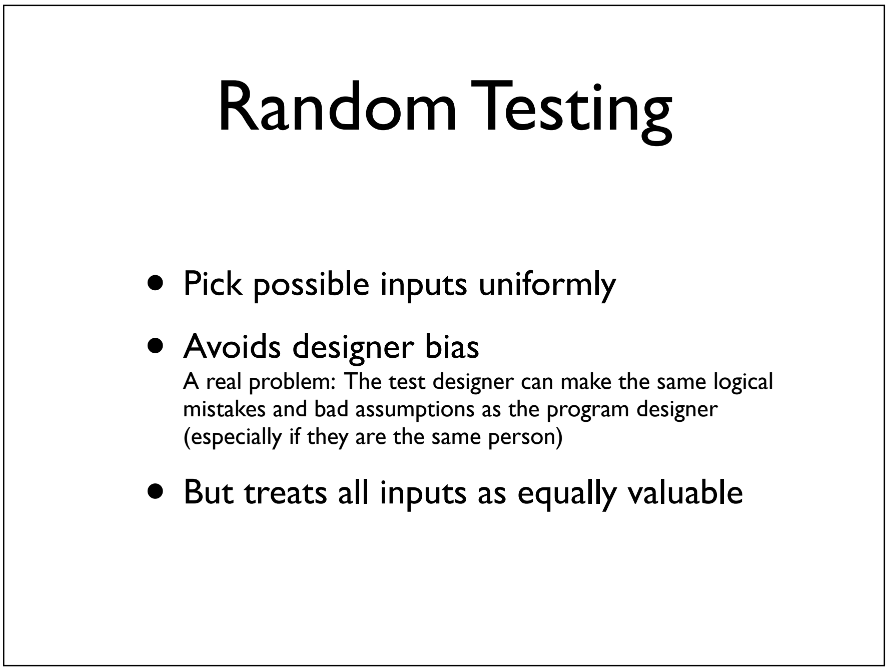


A Challenge

```
class Roots {
    // Solve ax² + bx + c = 0
    public roots(double a, double b, double c)
    { … }

    // Result: values for x
    double root_one, root_two;
}
```

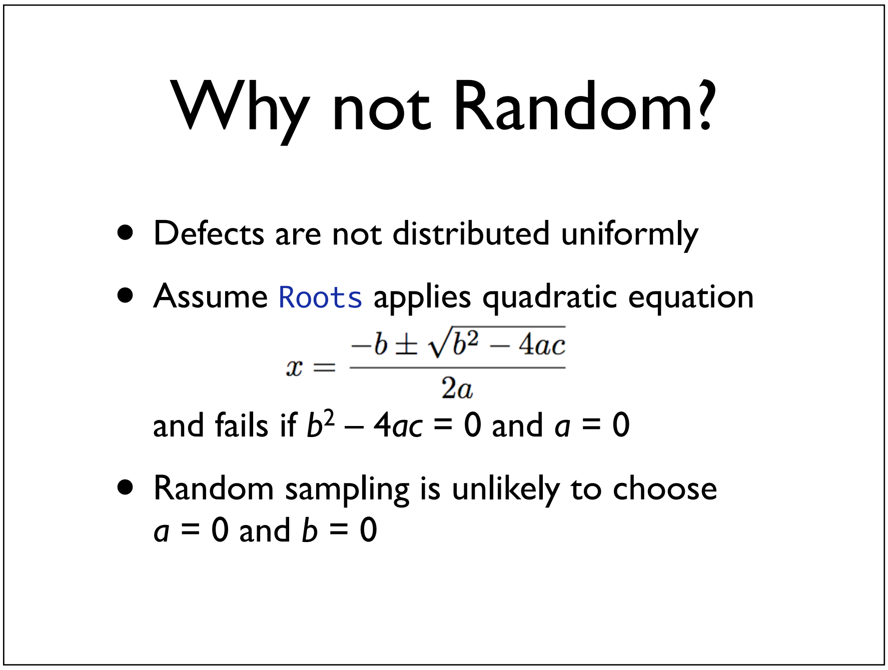
- Which values for *a, b, c* should we test?
  assuming a, b, c, were 32-bit integers, we'd have $(2^{32})^3 \approx 10^{28}$ legal inputs
  with 1.000.000.000.000 tests/s, we would still require 2.5 billion years



Random Testing

- Pick possible inputs uniformly
- Avoids designer bias
  A real problem: The test designer can make the same logical mistakes and bad assumptions as the program designer (especially if they are the same person)
- But treats all inputs as equally valuable

One might think that picking random samples might be a good idea.



Why not Random?

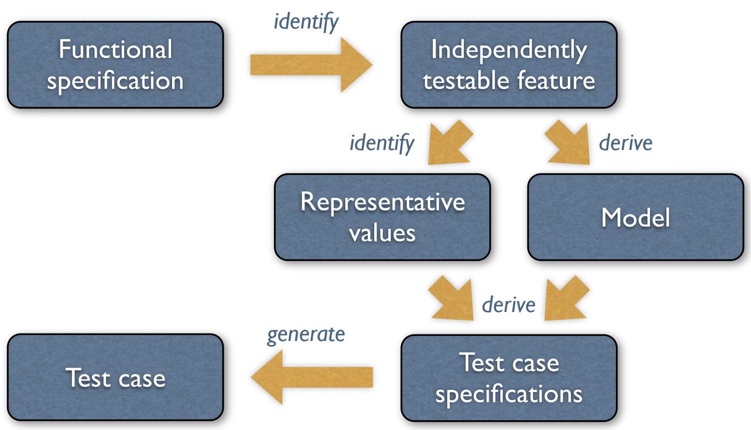
- Defects are not distributed uniformly
- Assume Roots applies quadratic equation

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

  and fails if $b^2 - 4ac = 0$ and $a = 0$
- Random sampling is unlikely to choose $a = 0$ and $b = 0$

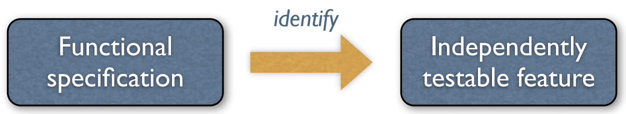
However, it is not. For one, we don't care for bias – we specifically want to search where it matters most. Second, random testing is unlikely to uncover specific defects. Therefore, we go for *functional testing.*

Systematic Functional Testing



The main steps of a systematic approach to functional program testing (from Pezze + Young, “Software Testing and Analysis”, Chapter 10)

Testable Features



- Decompose system into *independently testable features* (ITF)
- An ITF need not correspond to units or subsystems of the software
- For system testing, ITFs are exposed through user interfaces or APIs

Testable Fatures

```
class Roots {
    // Solve ax² + bx + c = 0
    public roots(double a, double b, double c)
    { … }

    // Result: values for x
    double root_one, root_two;
}
```

- What are the independently testable features?

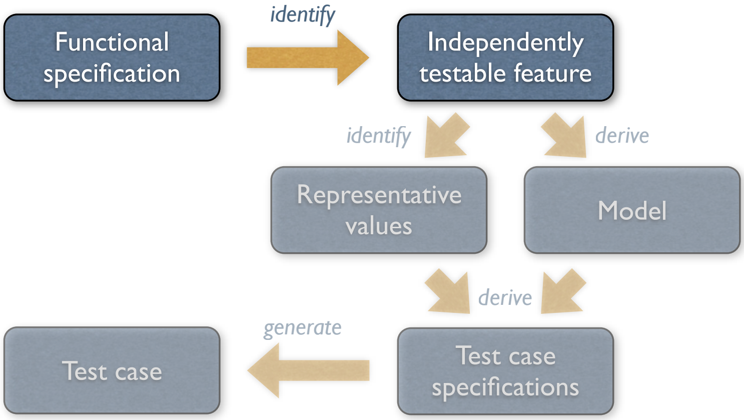
Just one – roots is a unit and thus provides exactly one single testable feature.

Testable Fatures

- Consider a multi-function calculator
- What are the independently testable features?

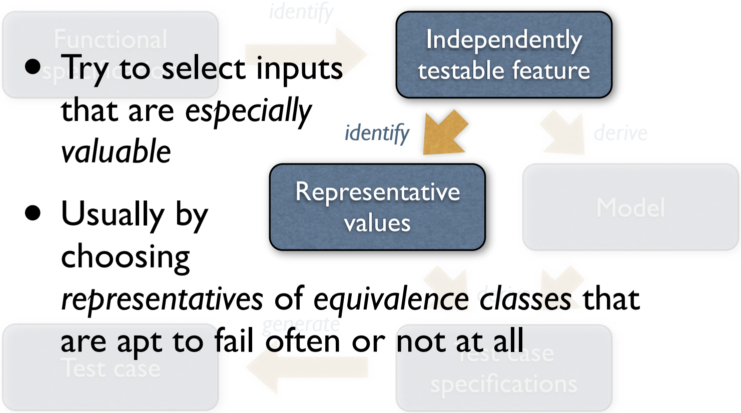
Every single function becomes an independently testable feature. Some functions (like memory access, for instance) are dependent on each other, though: to retrieve a value, you must first store it.
(Note how the calculator shows the #years required for the Roots calculation.)

Testable Features



The main steps of a systematic approach to functional program testing (from Pezze + Young, “Software Testing and Analysis”, Chapter 10)

Representative Values



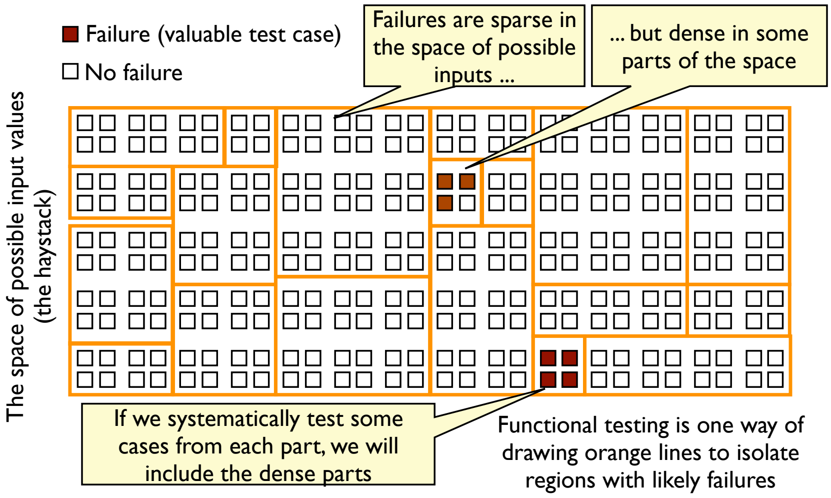
- Try to select inputs that are *especially valuable*
- Usually by choosing *representatives* of *equivalence classes* that are apt to fail often or not at all

The main steps of a systematic approach to functional program testing (from Pezze + Young, “Software Testing and Analysis”, Chapter 10)

Needles in a Haystack

- To find needles, look systematically
- We need to find out *what makes needles special*

Systematic Partition Testing



🟥 Failure (valuable test case)
□ No failure
The space of possible input values (the haystack)

Failures are sparse in the space of possible inputs ...

... but dense in some parts of the space

If we systematically test some cases from each part, we will include the dense parts

Functional testing is one way of drawing orange lines to isolate regions with likely failures

We can think of all the possible input values to a program as little boxes ... white boxes that the program processes correctly, and colored boxes on which the program fails. Our problem is that there are a lot of boxes ... a huge number, and the colored boxes are just an infinitesimal fraction of the whole set. If we reach in and pull out boxes at random, we are unlikely to find the colored ones. Systematic testing says: Let's not pull them out at random. Let's first subdivide the big bag of boxes into smaller groups (the pink lines), and do it in a way that tends to concentrate the colored boxes in a few of the groups. The number of groups needs to be much smaller than the number of boxes, so that we can systematically reach into each group to pick one or a few boxes.

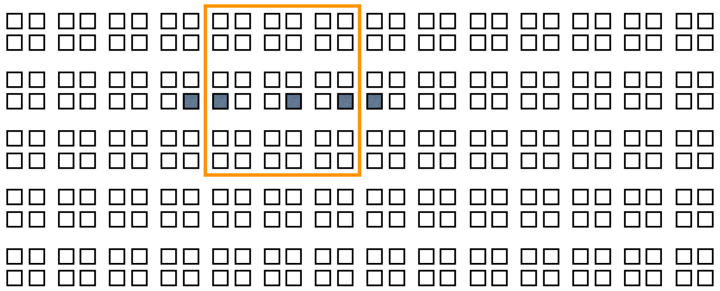
Equivalence Partitioning

Input condition	Equivalence classes
range	one valid, two invalid (larger and smaller)
specific value	one valid, two invalid (larger and smaller)
member of a set	one valid, one invalid
boolean	one valid, one invalid

How do we choose equivalence classes? The key is to examine input conditions from the spec. Each input condition induces an equivalence class – valid and invalid inputs.

Boundary Analysis

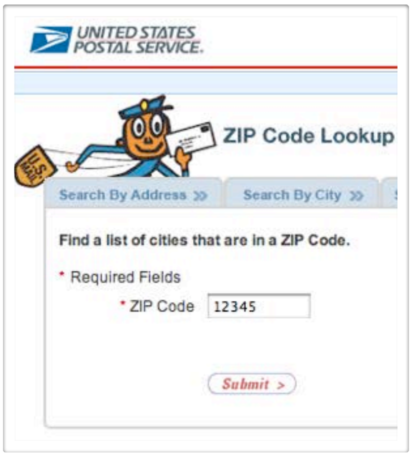
□ Possible test case



- Test at *lower range* (valid and invalid), at *higher range* (valid and invalid), and at *center*

How do we choose representatives rom equivalence classes? A greater number of errors occurs at the boundaries of an equivalence class rather than at the “center”. Therefore, we specifically look for values that are at the boundaries – both of the input domain as well as at the output.

Example: ZIP Code



Find a list of cities that are in a ZIP Code.

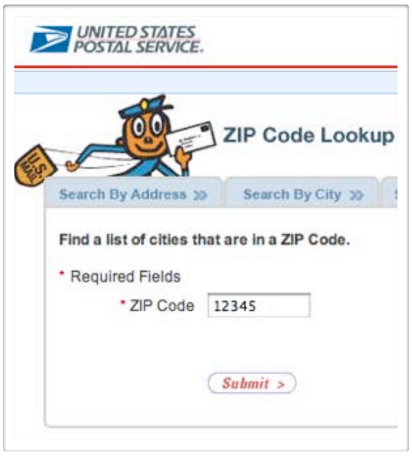
* Required Fields

* ZIP Code 12345

- Input: 5-digit ZIP code
- Output: list of cities
- What are representative values to test?

(from Pezze + Young, “Software Testing and Analysis”, Chapter 10)

Valid ZIP Codes



Find a list of cities that are in a ZIP Code.

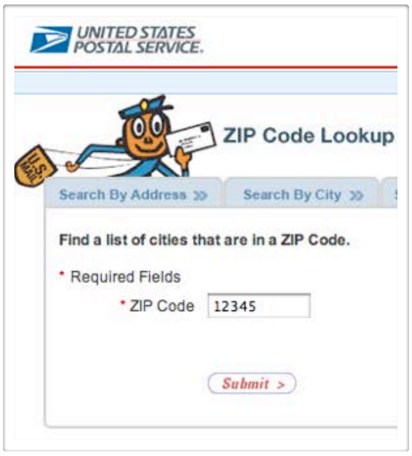
* Required Fields

* ZIP Code 12345

1. with 0 cities as output
(0 is boundary value)
2. with 1 city as output
3. with many cities as output

(from Pezze + Young, “Software Testing and Analysis”, Chapter 10)

Invalid ZIP Codes



Find a list of cities that are in a ZIP Code.

* Required Fields

* ZIP Code 12345

4. empty input
5. 1–4 characters
   (4 is boundary value)
6. 6 characters
   (6 is boundary value)
7. very long input
8. no digits
9. non-character data

(from Pezze + Young, “Software Testing and Analysis”, Chapter 10)

“Special” ZIP Codes

- How about a ZIP code that reads

```
12345‘; DROP TABLE orders; SELECT
* FROM zipcodes WHERE ‘zip’ = ‘
```

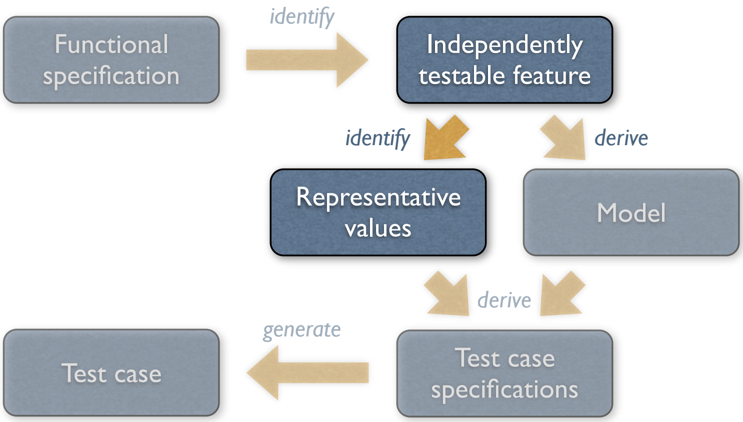
- Or a ZIP code with 65536 characters…
- This is security testing

Gutjahr’s Hypothesis

Partition testing
is more effective
than random testing.

Generally, random inputs are easier to generate, but less likely to cover parts of the specification or the code. See Gutjahr (1999) in IEEE Transactions on Software Engineering 25, 5 (1999), 661-667

Representative Values



Functional specification

identify

Independently testable feature

identify

derive

Representative values

Model

derive

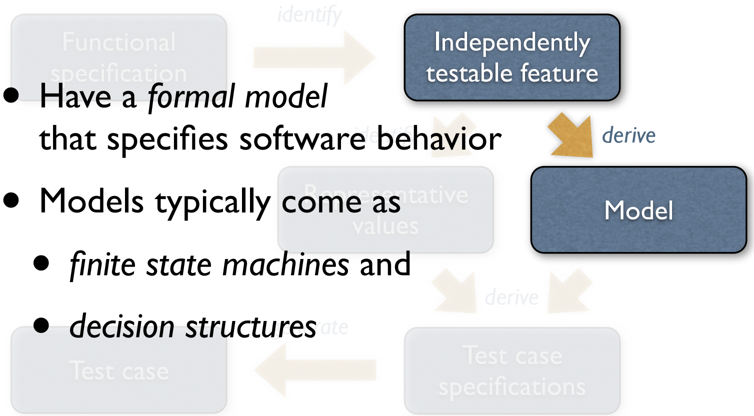
generate

Test case

Test case specifications

The main steps of a systematic approach to functional program testing (from Pezze + Young, “Software Testing and Analysis”, Chapter 10)

Model-Based Testing



Functional specification

identify

Independently testable feature

derive

Representative values

Model

derive

generate

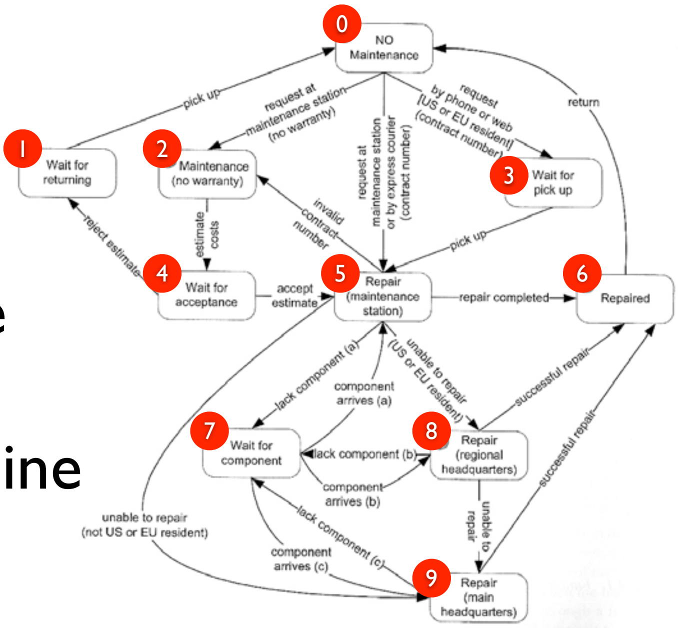
Test case

Test case specifications

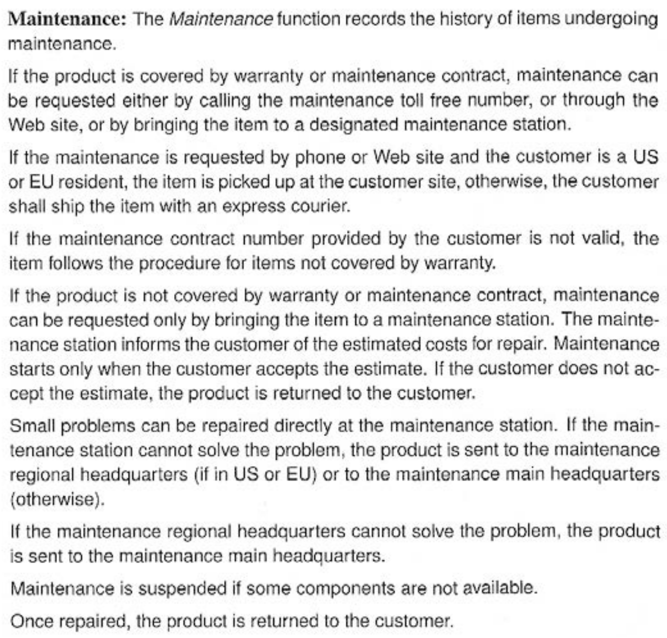
- Have a *formal model* that specifies software behavior
- Models typically come as
  - *finite state machines* and
  - *decision structures*

The main steps of a systematic approach to functional program testing (from Pezze + Young, “Software Testing and Analysis”, Chapter 10)

Finite State Machine



As an example, consider these steps modeling a product maintenance process…
(from Pezze + Young, “Software Testing and Analysis”, Chapter 14)



Maintenance: The *Maintenance* function records the history of items undergoing maintenance.

If the product is covered by warranty or maintenance contract, maintenance can be requested either by calling the maintenance toll free number, or through the Web site, or by bringing the item to a designated maintenance station.

If the maintenance is requested by phone or Web site and the customer is a US or EU resident, the item is picked up at the customer site, otherwise, the customer shall ship the item with an express courier.

If the maintenance contract number provided by the customer is not valid, the item follows the procedure for items not covered by warranty.

If the product is not covered by warranty or maintenance contract, maintenance can be requested only by bringing the item to a maintenance station. The maintenance station informs the customer of the estimated costs for repair. Maintenance starts only when the customer accepts the estimate. If the customer does not accept the estimate, the product is returned to the customer.

Small problems can be repaired directly at the maintenance station. If the maintenance station cannot solve the problem, the product is sent to the maintenance regional headquarters (if in US or EU) or to the maintenance main headquarters (otherwise).

If the maintenance regional headquarters cannot solve the problem, the product is sent to the maintenance main headquarters.

Maintenance is suspended if some components are not available.

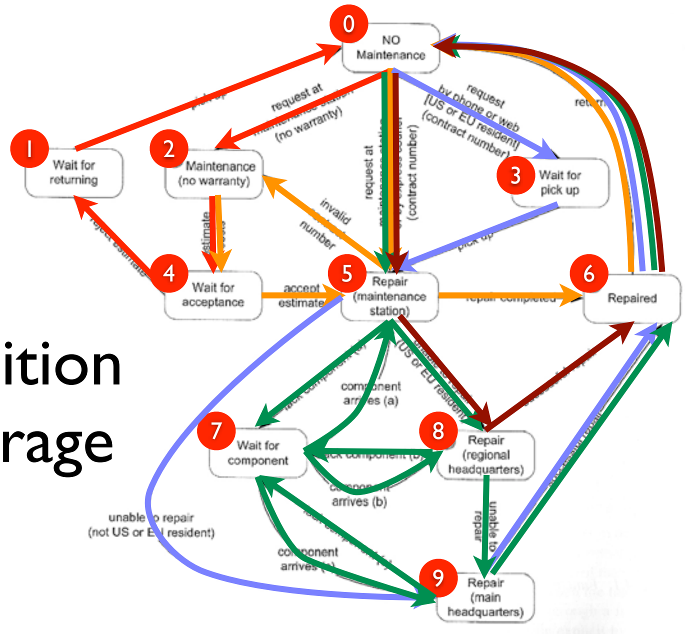
Once repaired, the product is returned to the customer.

…based on these (informal) requirements
(from Pezze + Young, “Software Testing and Analysis”, Chapter 14)

Coverage Criteria

- *Path coverage:* Tests cover every path
  Not feasible in practice due to infinite number of paths
- *State coverage:* Every node is executed
  A minimum testing criterion
- *Transition coverage:* Every edge is executed
  Typically, a good coverage criterion to aim for

Transition Coverage



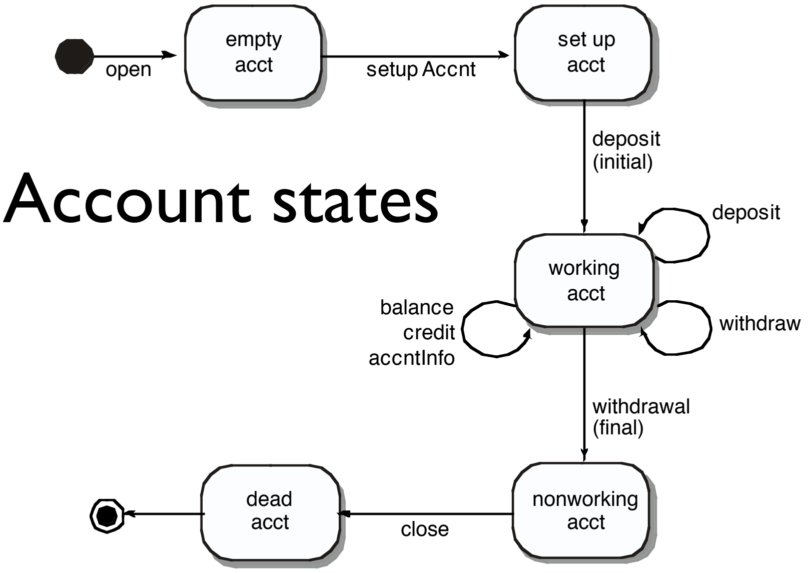
With five test cases (one color each), we can achieve transition coverage
(from Pezze + Young, “Software Testing and Analysis”, Chapter 14)

State-based Testing

- Protocols (e.g., network communication)
- GUIs (sequences of interactions)
- Objects (methods and states)

Finite state machines can be used to model for a large variety of behaviors – and thus serve as a base for testing.

Account states

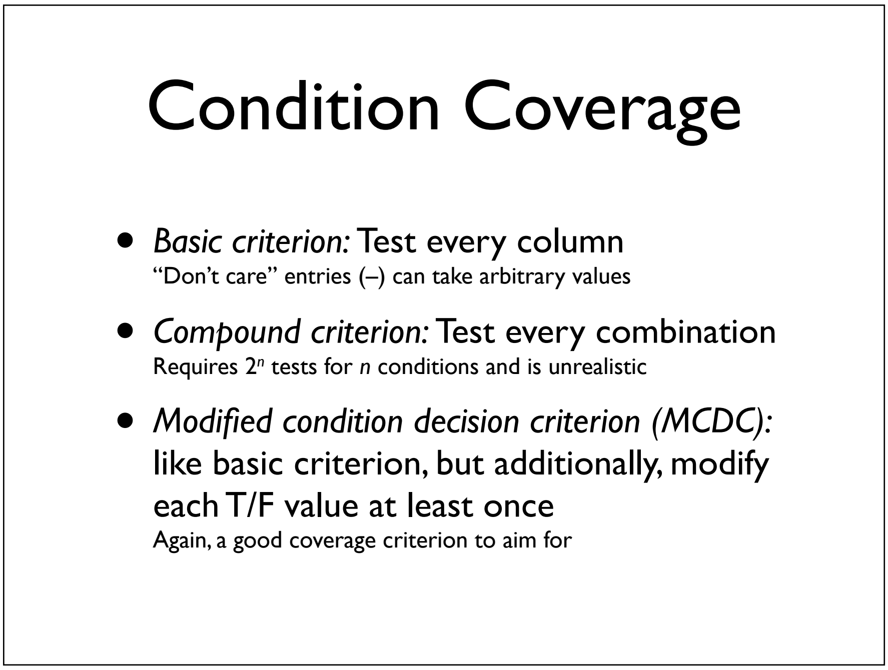


Here's an example of a finite state machine representing an Account class going through a number of states. Transition coverage means testing each Account method once.
(From Pressman, "Software Engineering – a practitioner's approach", Chapter 14)

Decision Tables

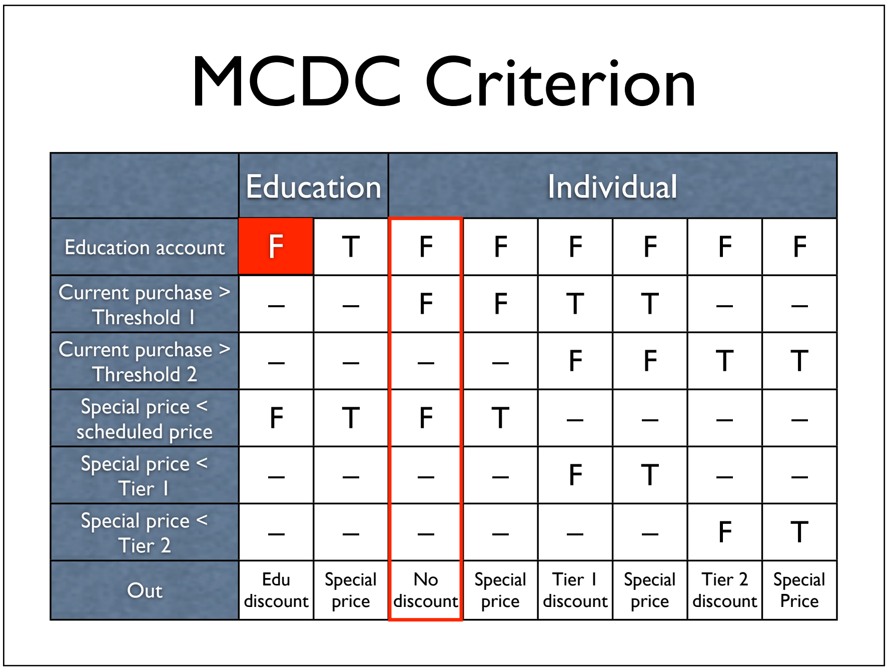
	Education		Individual					
Education account	T	T	F	F	F	F	F	F
Current purchase > Threshold 1	–	–	F	F	T	T	–	–
Current purchase > Threshold 2	–	–	–	–	F	F	T	T
Special price < scheduled price	F	T	F	T	–	–	–	–
Special price < Tier 1	–	–	–	–	F	T	–	–
Special price < Tier 2	–	–	–	–	–	–	F	T
Out	Edu discount	Special price	No discount	Special price	Tier 1 discount	Special price	Tier 2 discount	Special Price

A decision table describes under which conditions a specific outcome comes to be. This decision table, for instance, determines the discount for a purchase, depending on specific thresholds for the amount purchased.
(from Pezze + Young, "Software Testing and Analysis", Chapter 14)



Condition Coverage

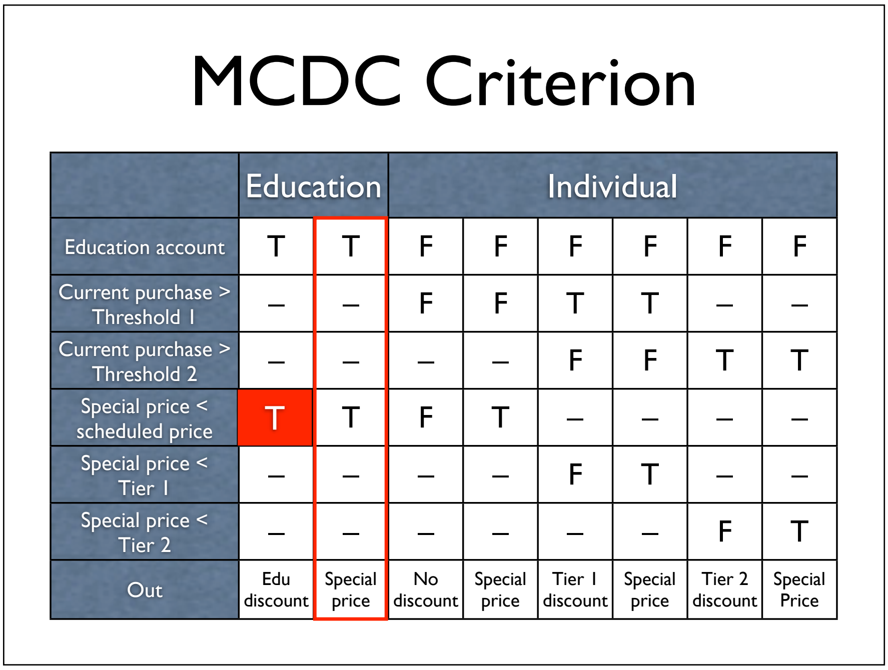
- *Basic criterion:* Test every column
  "Don't care" entries (–) can take arbitrary values
- *Compound criterion:* Test every combination
  Requires 2^n tests for *n* conditions and is unrealistic
- *Modified condition decision criterion (MCDC):* like basic criterion, but additionally, modify each T/F value at least once
  Again, a good coverage criterion to aim for



MCDC Criterion

	Education		Individual					
Education account	F	T	F	F	F	F	F	F
Current purchase > Threshold 1	–	–	F	F	T	T	–	–
Current purchase > Threshold 2	–	–	–	–	F	F	T	T
Special price < scheduled price	F	T	F	T	–	–	–	–
Special price < Tier 1	–	–	–	–	F	T	–	–
Special price < Tier 2	–	–	–	–	–	–	F	T
Out	Edu discount	Special price	No discount	Special price	Tier 1 discount	Special price	Tier 2 discount	Special Price

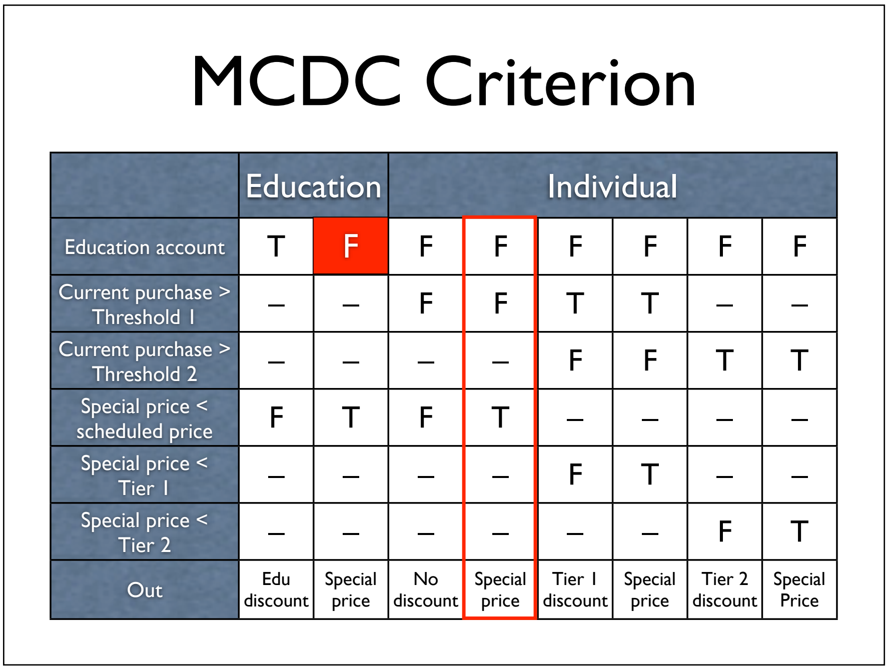
We modify the individual values in column 1 and 2 to generate four additional test cases – but these are already tested anyway. For instance, the modified values in column 1 are already tested in column 3.
(from Pezze + Young, "Software Testing and Analysis", Chapter 14)



MCDC Criterion

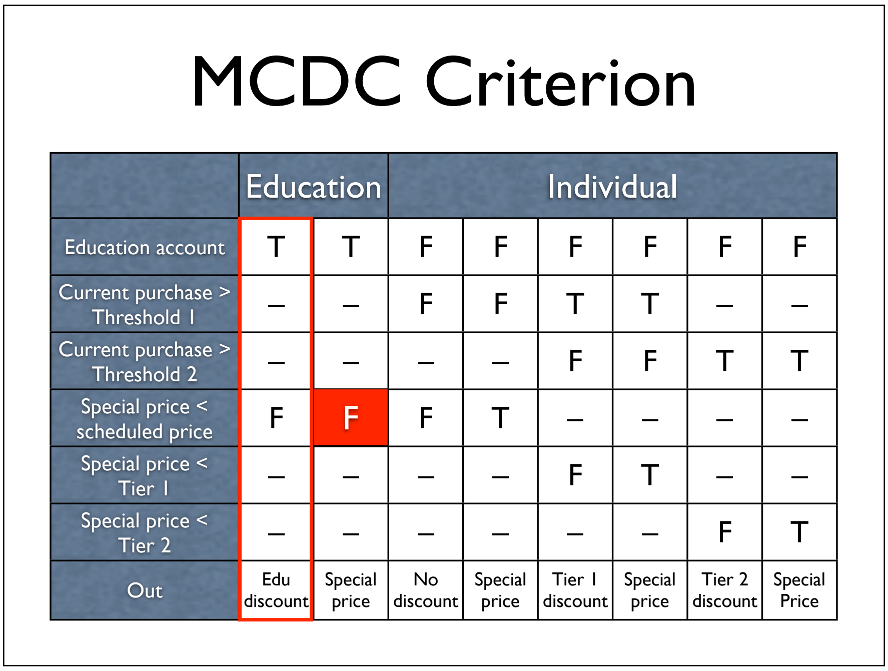
	Education		Individual					
Education account	T	T	F	F	F	F	F	F
Current purchase > Threshold 1	–	–	F	F	T	T	–	–
Current purchase > Threshold 2	–	–	–	–	F	F	T	T
Special price < scheduled price	T	T	F	T	–	–	–	–
Special price < Tier 1	–	–	–	–	F	T	–	–
Special price < Tier 2	–	–	–	–	–	–	F	T
Out	Edu discount	Special price	No discount	Special price	Tier 1 discount	Special price	Tier 2 discount	Special Price

This also applies to changing the other values, so adding additional test cases is not necessary in this case.
(from Pezze + Young, "Software Testing and Analysis", Chapter 14)



MCDC Criterion

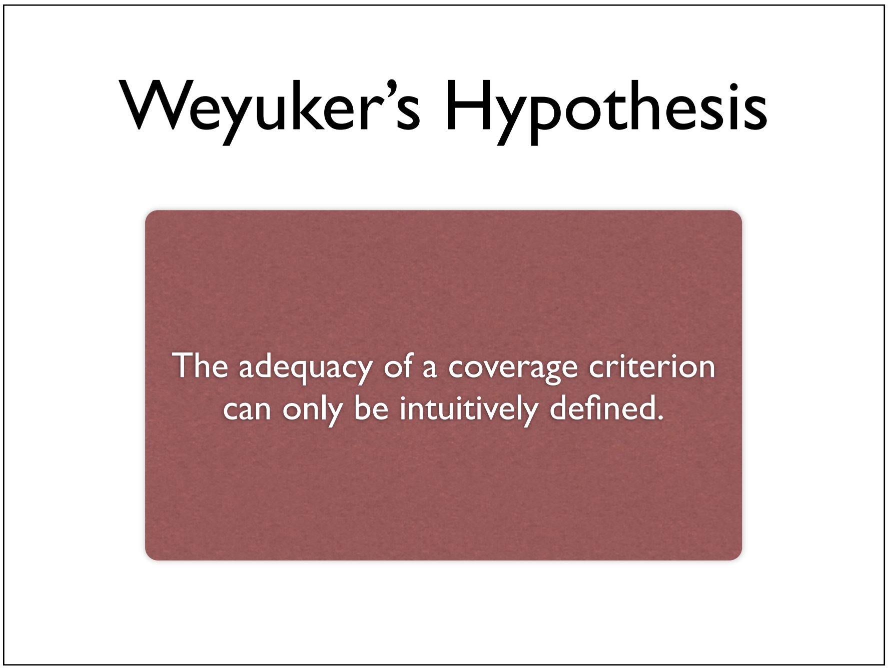
	Education		Individual					
Education account	T	F	F	F	F	F	F	F
Current purchase > Threshold 1	–	–	F	F	T	T	–	–
Current purchase > Threshold 2	–	–	–	–	F	F	T	T
Special price < scheduled price	F	T	F	T	–	–	–	–
Special price < Tier 1	–	–	–	–	F	T	–	–
Special price < Tier 2	–	–	–	–	–	–	F	T
Out	Edu discount	Special price	No discount	Special price	Tier 1 discount	Special price	Tier 2 discount	Special Price



MCDC Criterion

	Education		Individual					
Education account	T	T	F	F	F	F	F	F
Current purchase > Threshold 1	–	–	F	F	T	T	–	–
Current purchase > Threshold 2	–	–	–	–	F	F	T	T
Special price < scheduled price	F	F	F	T	–	–	–	–
Special price < Tier 1	–	–	–	–	F	T	–	–
Special price < Tier 2	–	–	–	–	–	–	F	T
Out	Edu discount	Special price	No discount	Special price	Tier 1 discount	Special price	Tier 2 discount	Special Price

However, if we had not (yet) tested the individual accounts, the MC/DC criterion would have uncovered them. (from Pezze + Young, “Software Testing and Analysis”, Chapter 14)

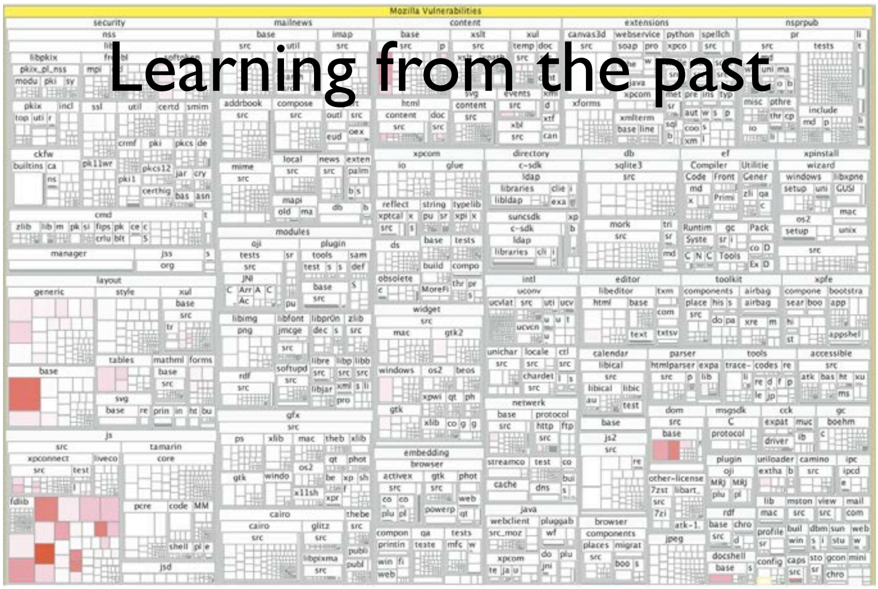


Weyuker’s Hypothesis

The adequacy of a coverage criterion can only be intuitively defined.

Established by a number of studies done by E. Weyuker at AT&T. “Any explicit relationship between coverage and error detection would mean that we have a fixed distribution of errors over all statements and paths, which is clearly not the case”.

Learning from the past



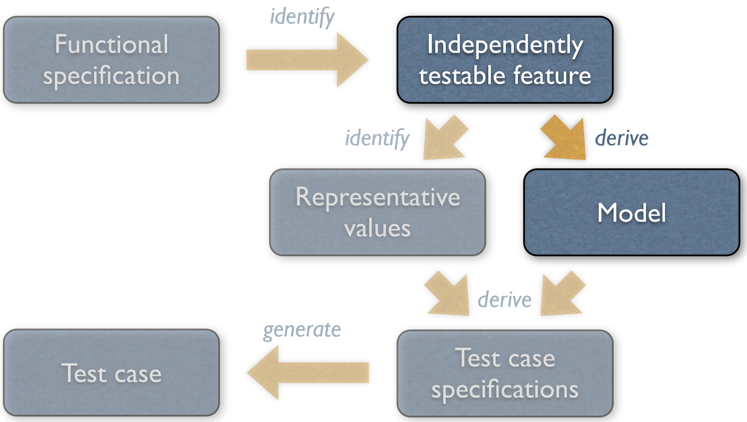
To decide where to put most effort in testing, one can also examine the past – i.e., where did most defects occur in the past. The above picture shows the distribution of security vulnerabilities in Firefox – the redder a rectangle, the more vulnerabilities, and therefore a likely candidate for intensive testing. The group of Andreas Zeller at Saarland University researches how to mine such information automatically and how to predict future defects.

Pareto's Law

Approximately 80% of defects come from 20% of modules

Evidence: several studies, including Zeller's own evidence :-)

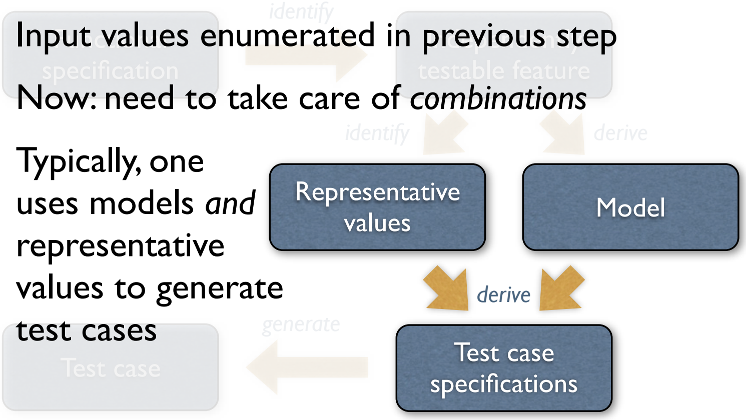
Model-Based Testing



The main steps of a systematic approach to functional program testing (from Pezze + Young, "Software Testing and Analysis", Chapter 10)

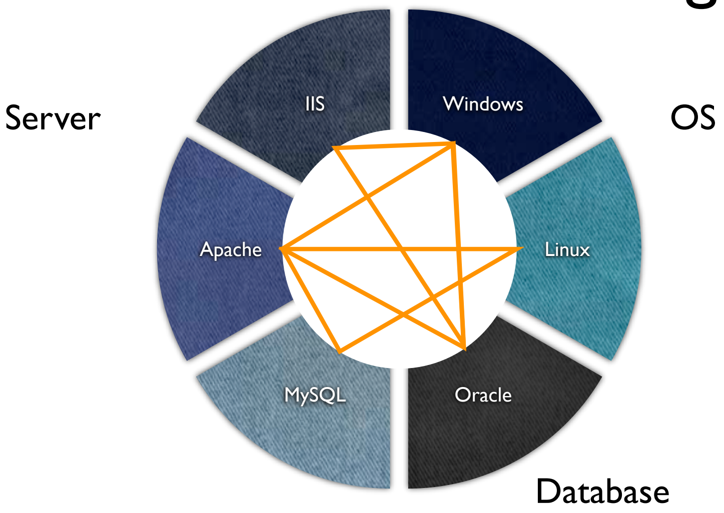
Deriving Test Case Specs

- Input values enumerated in previous step
- Now: need to take care of *combinations*
- Typically, one uses models *and* representative values to generate test cases



The main steps of a systematic approach to functional program testing (from Pezze + Young, “Software Testing and Analysis”, Chapter 10)

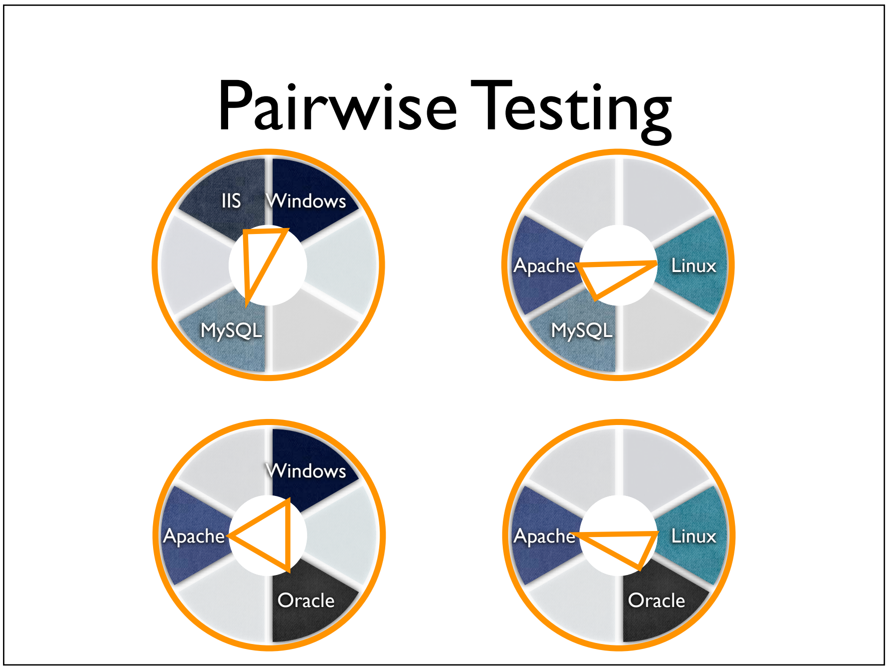
Combinatorial Testing



Many domains come as a combination of individual inputs. We therefore need to cope with a combinatorial explosion.

Combinatorial Testing

- Eliminate invalid combinations
  IIS only runs on Windows, for example
- Cover *all pairs* of combinations
  such as MySQL on Windows and Linux
- Combinations typically generated automatically
  and – hopefully – tested automatically, too



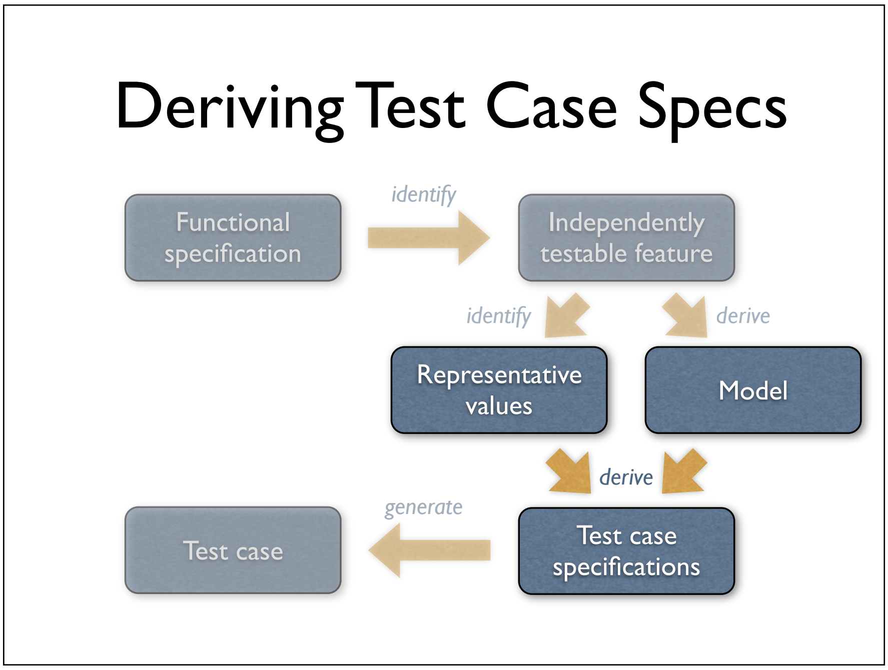
Pairwise Testing

Pairwise testing means to cover every single pair of configurations

Testing environment

- Millions of configurations
- Testing on dozens of different machines
- All needed to find & reproduce problems

In practice, such testing needs hundreds and hundreds of PCs in every possible configuration – Microsoft, for instance, has entire buildings filled with every hardware imaginable
Source: http://www.ci.newton.ma.us/MIS/Network.htm



Deriving Test Case Specs

Functional specification → *identify* → Independently testable feature

Independently testable feature → *identify* → Representative values

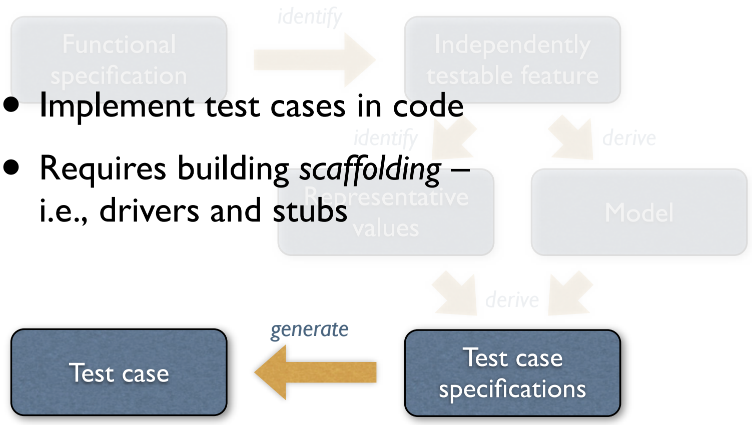
Independently testable feature → *derive* → Model

Representative values, Model → *derive* → Test case specifications

Test case specifications → *generate* → Test case

The main steps of a systematic approach to functional program testing (from Pezze + Young, “Software Testing and Analysis”, Chapter 10)

Deriving Test Cases


- Implement test cases in code
- Requires building *scaffolding* – i.e., drivers and stubs

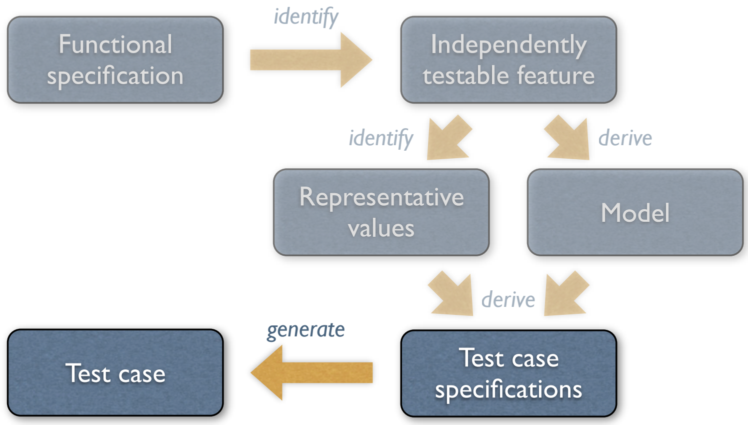
The main steps of a systematic approach to functional program testing (from Pezze + Young, "Software Testing and Analysis", Chapter 10)

Unit Tests

- Directly access units (= classes, modules, components…) at their programming interfaces
- Encapsulate a set of tests as a single syntactical unit
- Available for all programming languages (JUNIT for Java, CPPUNIT for C++, etc.)

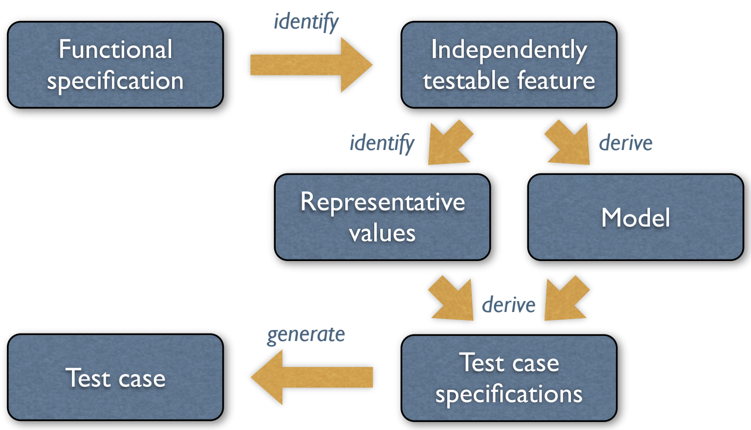
Here's an example for automated unit tests – the well-known JUnit

Deriving Test Cases

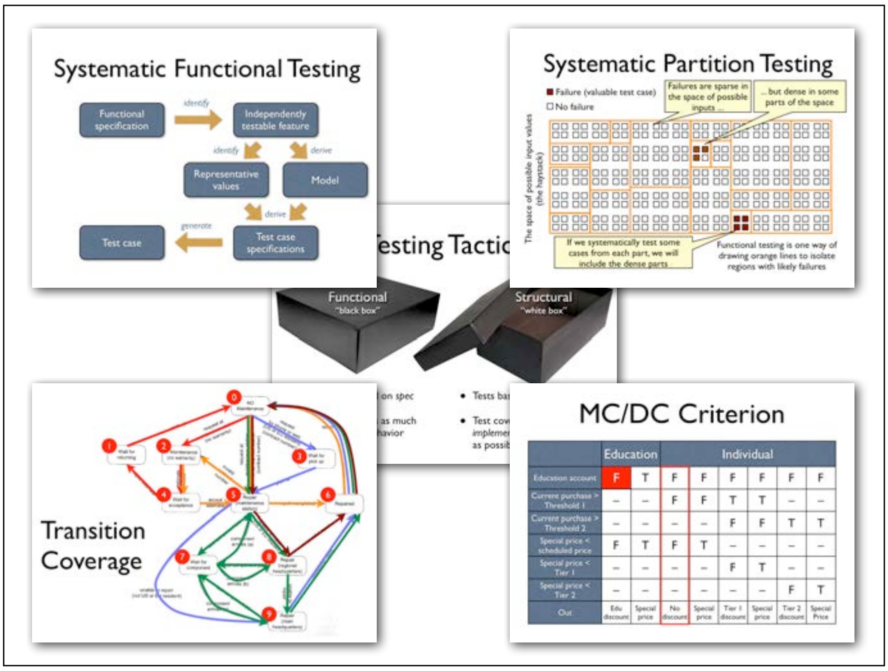


The main steps of a systematic approach to functional program testing (from Pezze + Young, "Software Testing and Analysis", Chapter 10)

Systematic Functional Testing



The main steps of a systematic approach to functional program testing (from Pezze + Young, "Software Testing and Analysis", Chapter 10)



Systematic Functional Testing

Systematic Partition Testing

■ Failure (valuable test case)

□ No failure

Failures are sparse in the space of possible inputs ...

... but dense in some parts of the space

If we systematically test some cases from each part, we will include the dense parts

Functional testing is one way of drawing orange lines to isolate regions with likely failures

Transition Coverage

MC/DC Criterion

	Education		Individual					
Education account	F	T	F	F	F	F	F	F
Current purchase > Threshold 1	–	–	F	F	T	T	–	–
Current purchase > Threshold 2	–	–	–	–	F	F	T	T
Special price < scheduled price	F	T	F	T	–	–	–	–
Special price < Tier 1	–	–	–	–	F	T	–	–
Special price < Tier 2	–	–	–	–	–	–	F	T
Out	Edu discount	Special price	No discount	Special price	Tier 1 discount	Special price	Tier 2 discount	Special Price