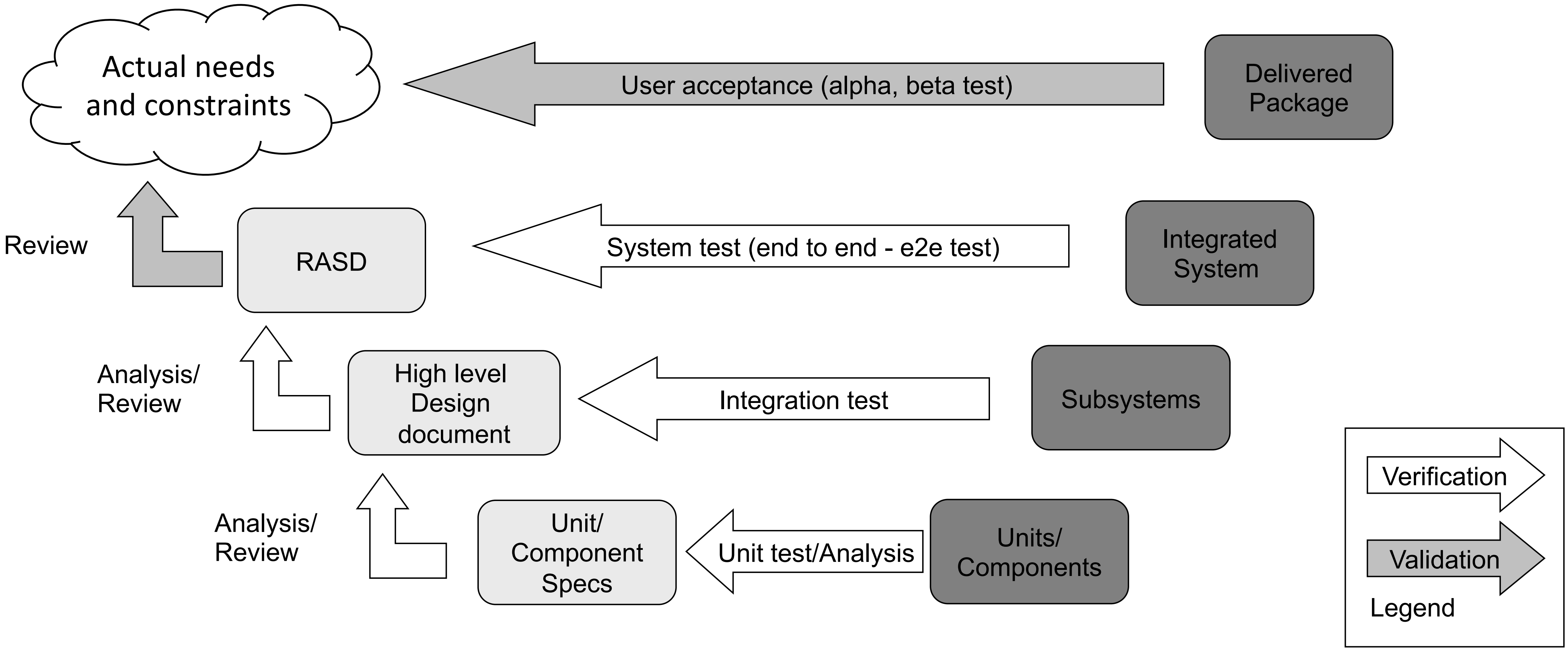
Verification & Validation

Analysis: symbolic execution

Testing: terminology, types of testing activities

Verification at which level? (V model)



Main approaches: static vs dynamic analysis

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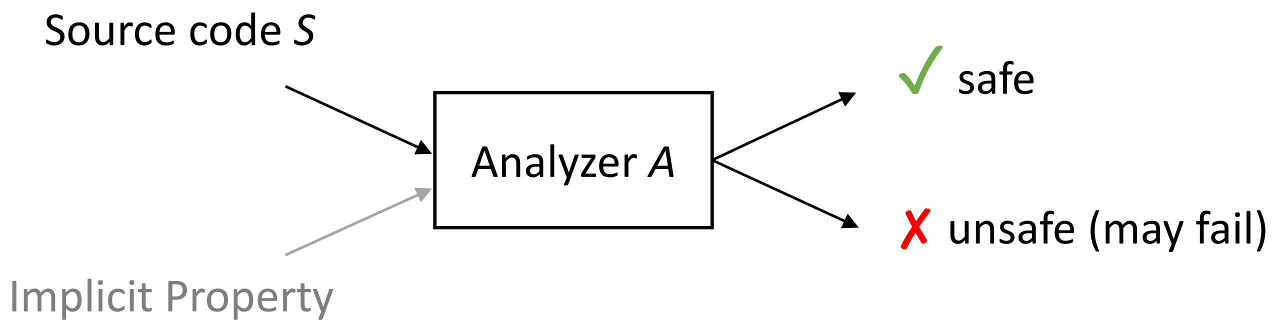
- Static Analysis
  - Done on source code without execution
  - Analysis is static but properties are dynamic
- Testing (dynamic analysis)
  - Done by executing the sources (usually by sampling)
  - Analysis of the actual behavior compared to an expected one

Static Analysis

- The very idea
  - Analyzes the source code
  - Each analyzer targets a fixed set of **hard-coded** (pre-defined, not custom) properties
  - Completely **automatic**
  - The output reports
    - **Safe** = no issues
    - **Unsafe** = potential issues



Static Analysis: properties

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- Checked properties are often general safety properties (absence of certain conditions that may yield errors)
- Examples:
  - No overflow for integer variables
  - No type errors
  - No null-pointer dereferencing
  - No out-of-bound array accesses
  - No race conditions
  - No useless assignments
  - No usage of undefined variables
  - No execution of specific paths

Static analysis: succesful stories

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[2017] *"Our strategy at Uber has been to use static code analysis tools to prevent null pointer exception crashes."*

Engineering NullAway, Uber's Open Source Tool for Detecting NullPointerExceptions on Android
https://www.uber.com/en-IT/blog/nullaway/

[2013] *"Each month, hundreds of potential bugs identified by Facebook Infer are fixed [. . .] before they are [. . .] deployed to people's phones."*

Facebook buys code-checking Silicon Roundabout startup Monoidics
https://www.theguardian.com/technology/2013/jul/18/facebook-buys-monoidics

More on Static vs Dynamic

- Static
  - at compile time – before execution
  - related to source code (or any other model of the software)
  - without execution of the software
  - on generic (or symbolic) inputs
- Dynamic
  - at runtime – during execution
  - related to software behavior
  - while executing the software
  - on specific inputs

- Static analysis: techniques, methods, tools used to infer properties of the dynamic behavior without explicitly running the software
  - It is a pessimistic technique

Static analysis tools

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- Various tools available
- The analyses are language-specific but many tools support multiple programming languages
- The first static analysis tool was a Unix utility, Lint, developed in 1978 for C programs. From this, simple static analysis is also called linting
- Lists of currently available tools are available from various sources:
  - https://en.wikipedia.org/wiki/List_of_tools_for_static_code_analysis
  - https://github.com/analysis-tools-dev/static-analysis

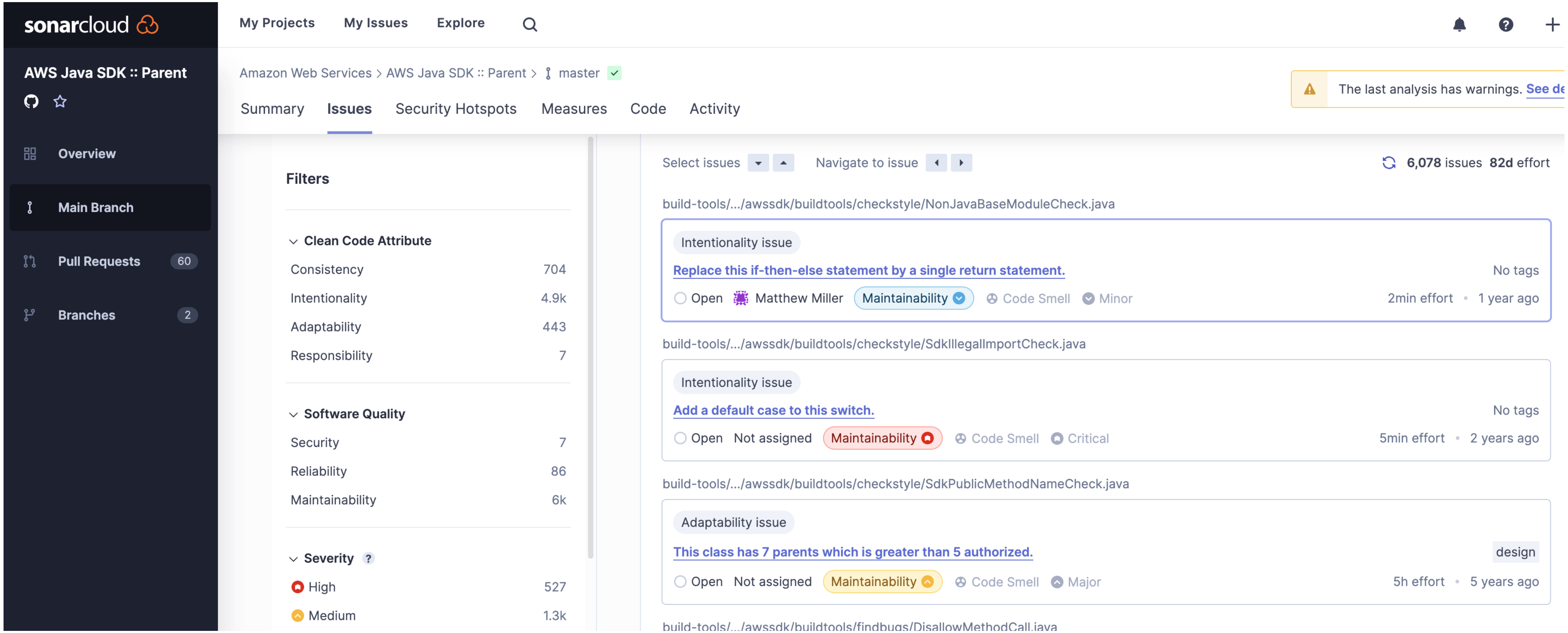
Comparing some static analysis tools

https://www.comparitech.com/net-admin/best-static-code-analysis-tools/

Tool/Features	SonarQube	Checkmarx	Synopsys Coverity	Micro Focus Fortify SCA	Veracode Static Analysis	Snyk Code
Language Support	Multiple	Multiple	Multiple	Multiple	Multiple	Multiple
Integrations	Various IDEs, CI/CD	Various IDEs, CI/CD	Various IDEs, CI/CD	Various IDEs, CI/CD	Various IDEs, CI/CD	Various IDEs, CI/CD
Free Trial	Yes	Yes	No	Yes	Yes	Yes
On-Premises/Cloud	Both	Both	Both	Both	Both	Cloud
Automated Scans	Yes	Yes	Yes	Yes	Yes	Yes
Compliance Reporting	Yes	Yes	Yes	Yes	Yes	Yes
Vulnerability Database	Yes	Yes	Yes	Yes	Yes	Yes
Real-Time Feedback	Yes	Yes	No	No	No	Yes

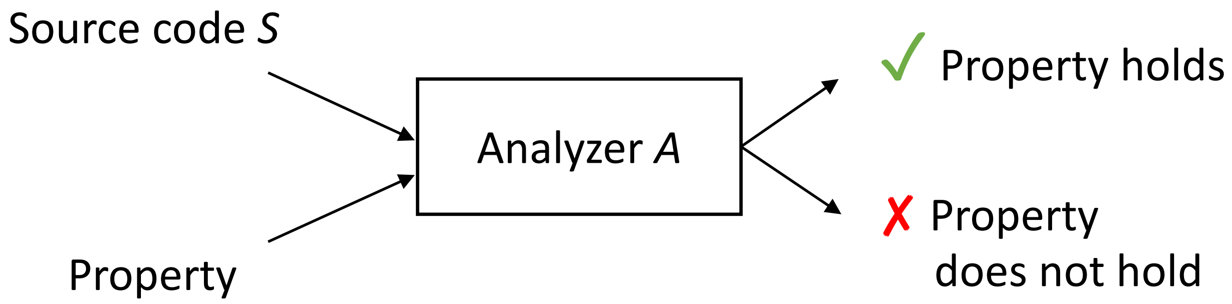
Example of issues report from SonarCloud/SonarQube

https://sonarcloud.io/project/issues?resolved=false&id=aws_aws-sdk-java-v2



Symbolic execution

- The very idea
  - Analyzes **real** source code
  - Analyzes **reachability** and **path feasibility** properties
  - Is **automatic**
  - **May fail** to analyze all possible paths
  - Can be used to **support testing**



Types of checked properties

- Reachability: does some execution of the program reach the location *l* in *S*?
  - Symbolic exec tries to **verify that *l* cannot be reached**, or alternatively **spots the condition under which *l* can be reached**

```
…
k:    try {
k+1:    …
l-1:  } catch (e) {
l:      /* error */
…     }
```

```
…
l-1: if (x < 0) {
l:     /* safe */
```

- Path feasibility: Is the given path *p* feasible?
  - Symbolic exec tries to **verify that *p* cannot be executed**, or alternatively **spots the condition under which *p* can be executed**

```
p = <0,1,…,k,…,n>
```

Symbolic state and path condition

- Symbolic execution executes programs on symbolic values
  - Symbolic states keep track of the (symbolic) value of variables

Inputs are initialized with symbolic (generic) values

```
0: void foo(int x, int y) {
1:     …
```

Symbolic state

variables

x	y
X	Y

<0>

Symbolic values

path

Symbolic state and path condition

- Symbolic execution executes programs on symbolic values
  - Symbolic states keep track of the (symbolic) value of variables

Executing a statement updates the symbolic state

```
0: void foo(int x, int y) {
1:    int z := x
```

Symbolic state

x	y	z
X	Y	X

<0,1>

Symbolic state and path condition

- Symbolic execution executes programs on symbolic values
  - Symbolic states keep track of the (symbolic) value of variables

Executing a branch splits the symbolic state
A path condition π represents the constraint of a path

```
0: void foo(int x, int y) {
1:   int z := x
2:   if (z < y)
```

Symbolic state

Condition at point 2 true:

x	y	z	π	
X	Y	X	$X<Y$	<0,1,2>

Condition at point 2 false:

x	y	z	π	
X	Y	X	$X \geq Y$	<0,1,2>

Symbolic state and path condition

- Symbolic execution executes programs on symbolic values
  - Symbolic states keep track of the (symbolic) value of variables

The execution continues along feasible paths (path condition π is satisfiable)

```
0: void foo(int x, int y) {
1:   int z := x
2:   if (z < y)
3:     z := z*2
```

Symbolic state

x	y	z	π
X	Y	2X	X<Y

<0,1,2,3>

Symbolic state and path condition

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- Symbolic execution executes programs on symbolic values
  - Symbolic states keep track of the (symbolic) value of variables

The execution continues along feasible paths (path condition π is satisfiable)

```
0: void foo(int x, int y) {
1:   int z := x
2:   if (z < y)
3:     z := z*2
4:   if (x < y && z >= y)
```

Symbolic state

Condition at point 4 true:

x	y	z	π
X	Y	2X	X<Y
			X<Y ∧ 2X≥Y

<0,1,2,3,4>

Condition at point 4 false:

x	y	z	π
X	Y	2X	X<Y
			X≥Y ∨ 2X<Y

<0,1,2,3,4>

Final states

- Possible outcomes of symbolic execution:
  - SAT exit (π is satisfiable): any satisfying assignment to variables in π is an **input** that satisfies the given property in a **concrete execution**
  - UNSAT exit (π is not satisfiable): the given property cannot be satisfied by **any concrete execution**
- **Example**: is location 5 reachable?

```
0: int foo(int x, int y) {
1:   int z := x
2:   if (z < y)
3:     z := z*2
4:   if (x < y && z >= y)
5:     print(z) //location
6: }
```

x	y	z	π
X	Y	2X	$X<Y$
			$X<Y \wedge 2X \geq Y$

<0,1,2,3,4,5>

SAT exit

Example of satisfying assignment: X = 2, Y = 3

Final states

- Possible outcomes of symbolic execution:
  - SAT exit (π is satisfiable): any satisfying assignment to variables in π is an **input** that satisfies the given property in a **concrete execution**
  - UNSAT exit (π is not satisfiable): the given property cannot be satisfied by **any concrete execution**
- **Example**: is path <0,1,2,4,5> feasible?

```
0: int foo(int x, int y) {
1:   int z := x
2:   if (z < y)
3:     z := z*2
4:   if (x < y && z >= y)
5:     print(z) //location
6: }
```

x	y	z	π	
X	Y	X	$X \geq Y$	<0,1,2,4>
			$X<Y \wedge X \geq Y$	

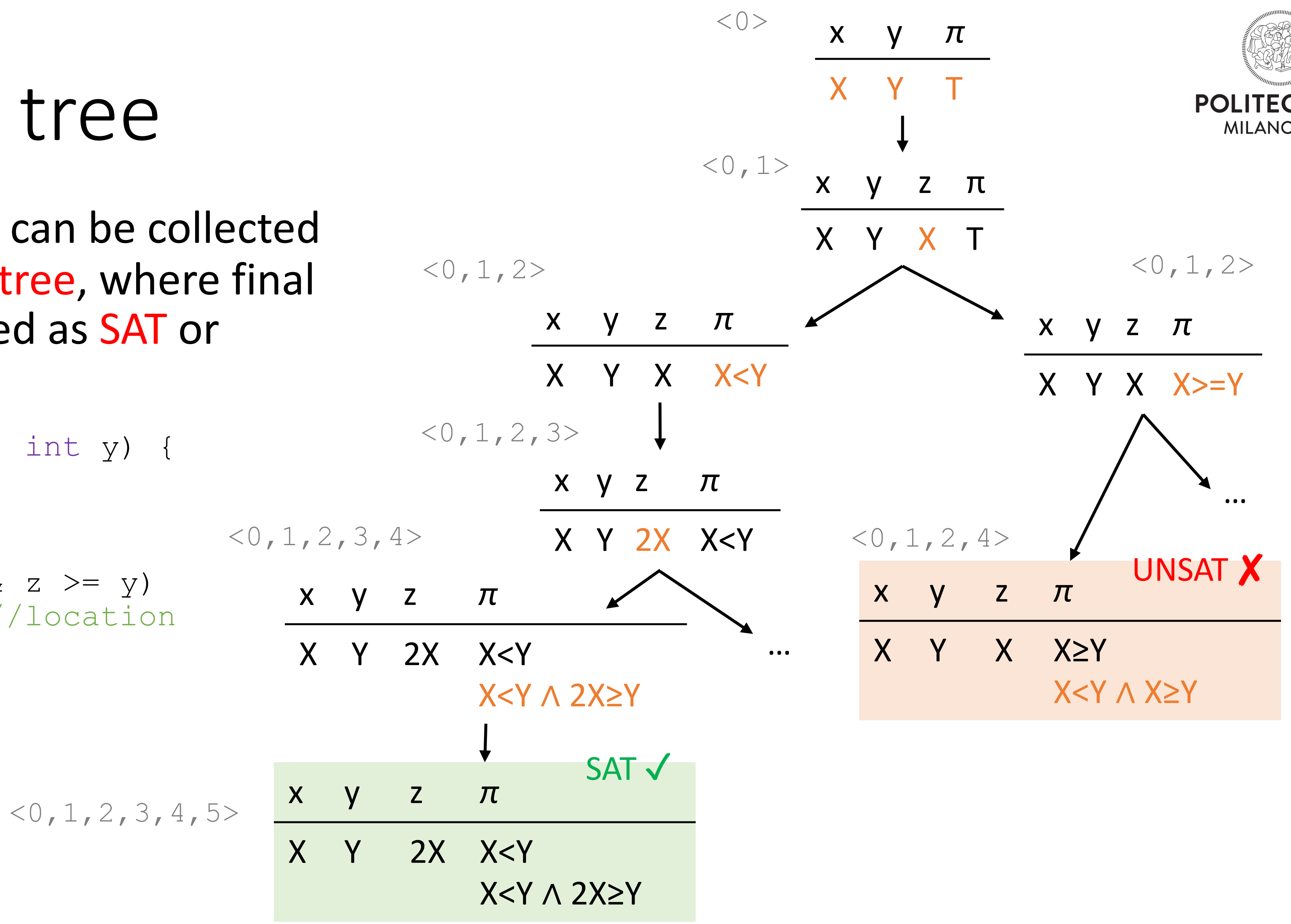
UNSAT exit

There is no satisfying assignment

Execution tree

- Execution paths can be collected in an execution tree, where final states are marked as SAT or UNSAT

```
0: int foo(int x, int y) {
1:   int z := x
2:   if (z < y)
3:     z := z*2
4:   if (x < y && z >= y)
5:     print(z) //location
6: }
```



Symbolic execution: exercise

- Consider the following program `bar`. Is the path `<0,1,2,3,4,5,8,2,3,4,7,8,2,10,11>` feasible?

```
0:  int bar( ) {
1:    int x := input()
2:    while (x > 0) {
3:      int y := 2*x
4:      if (x > 10)
5:        y := x - 1
6:      else
7:        x := x + 2
8:      x := x - 1
9:    }
10:   x := x - 1
11:   return x
12: }
```

`<0>`

x	y	π
		T

`<0,1>`

x	y	π
X		T

`<0,1,2>`

x	y	π
X		X>0

`<0,1,2,3>`

x	y	π
X	2X	X>0

`<0,1,2,3,4>`

x	y	π
X	2X	X>0 X>10

`<0,1,2,3,4,5>`

x	y	π
X	X-1	X>10

`<0,1,2,3,4,5,8>`

x	y	π
X-1	X-1	X>10

`<0,1,2,3,4,5,8,2>`

x	y	π
X-1	X-1	X>10 X-1>0

`<0,1,2,3,4,5,8,2,3>`

x	y	π
X-1	2(X-1)	X>10

`<0,1,2,3,4,5,8,2,3,4>`

x	y	π
X-1	2(X-1)	X>10 X-1≤10

Symbolic execution: exercise

- Consider the following program `bar`. Is the path `<0 1 2 3 4 5 8 2 3 4 7 8 2 10 11>` feasible?

```
0:   int bar( ) {
1:     int x := input()
2:     while (x > 0) {
3:       int y := 2*x
4:       if (x > 10)
5:         y := x - 1
6:       else
7:         x := x + 2
8:       x := x - 1
9:     }
10:    x := x - 1
11:    return x
11: }
```

`<0,1,2,3,4,5,8,2,3,4>`

x	y	π
$X-1$	$2(X-1)$	$X>10$
		$X\leq 11$

`<0,1,2,3,4,5,8,2,3,4,7>`

x	y	π
$X+1$	$2(X-1)$	$X>10$
		$X\leq 11$

`<0,1,2,3,4,5,8,2,3,4,7,8>`

x	y	π
X	$2(X-1)$	$X>10$
		$X\leq 11$

`<0,1,2,3,4,5,8,2,3,4,7,8,2>`

x	y	π
X	$2(X-1)$	$X>10$
		$X\leq 11$
		$X\leq 0$

- Conclusion: path `<0,1,2,3,4,5,8,2,3,4,7,8,2,10,11>` is unfeasible

Symbolic execution: weaknesses

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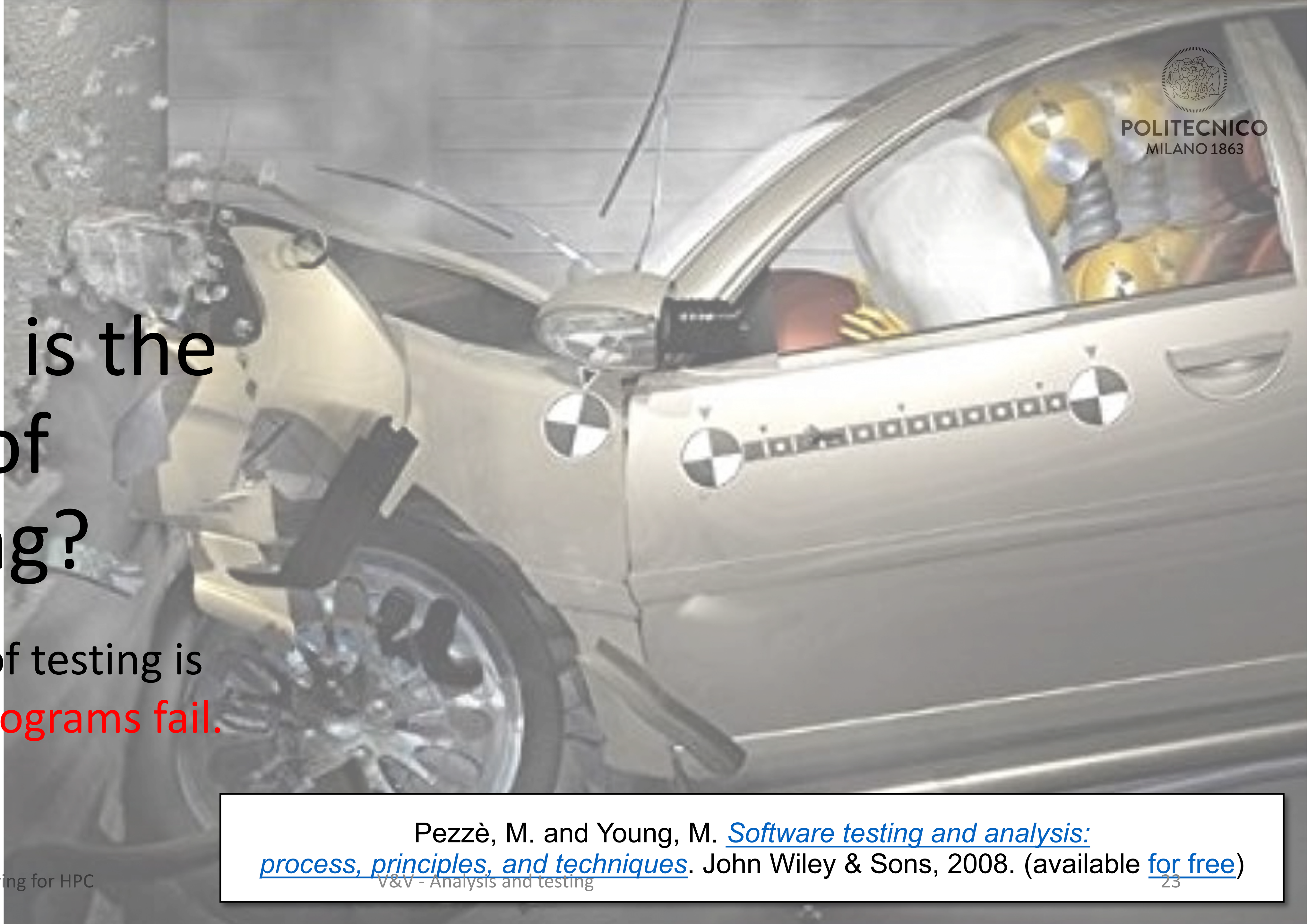
- It seems symbolic execution can be used to verify the correctness of any program, however…
- Limitations
  - Path conditions may be too complex for constraint solvers
    - Solvers are very good at checking linear constraints
    - It is harder for them to reason on non-linear arithmetic, bit-wise operations, string manipulation
  - Impossible/hard to use when number of paths to be explored is infinite/huge
    - unbounded loops give rise to infinite sets of paths
    - Even if set of paths is finite, checking all loops is expensive/unfeasible in practice
      - rule of thumb: approximate the analysis by considering 0, 1, and 2 iterations
  - There may be external code
    - Sources not available (e.g., pre-compiled library) → unknown behavior for the solver



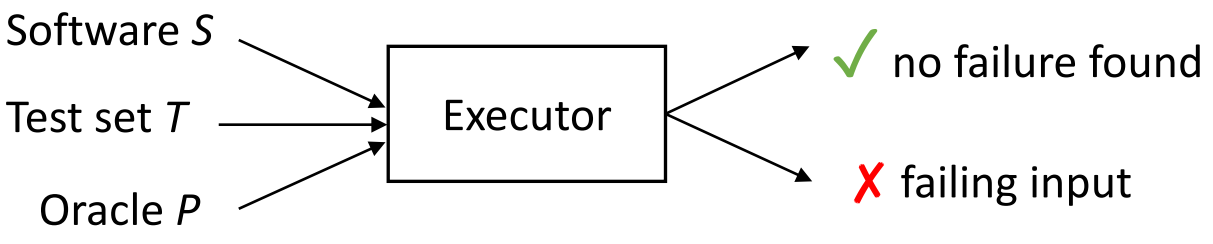
What is the goal of testing?

The goal of testing is
making programs fail.

Pezzè, M. and Young, M. *Software testing and analysis: process, principles, and techniques*. John Wiley & Sons, 2008. (available for free)

Testing, aka dynamic analysis

- The very idea
  - Analyzes program behavior
  - Properties are encoded as executable oracles, that represent
    - expected outputs, desired conditions (assertions)
  - It can run only finite sets of test cases → it's not exhaustive verification
  - Failures come with concrete inputs that trigger them
  - Execution is automatic (definition of test cases and oracles may not)



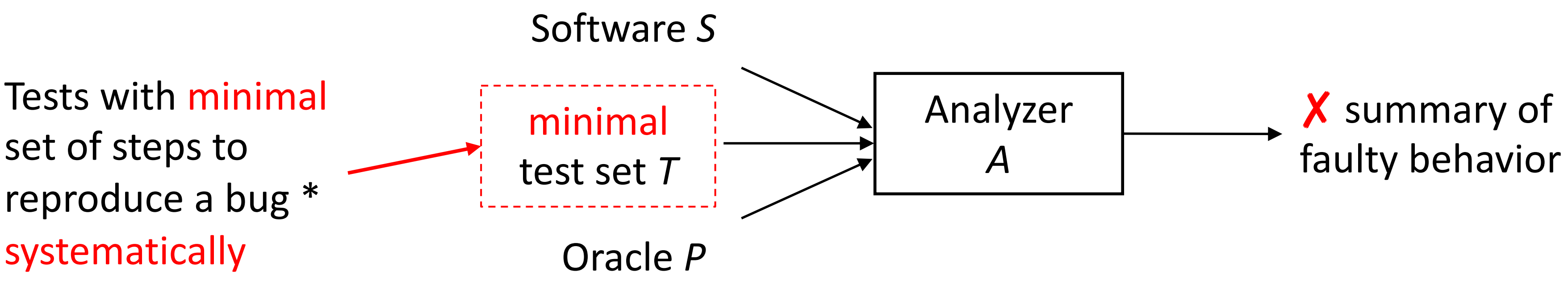
What is the goal of testing?

The main goal of testing is making programs fail

- Other common goals
  - Exercise different parts of a program to increase coverage
  - Make sure the interaction between components works (integration testing)
  - Support fault localization and error removal (debugging)
  - Ensure that bugs introduced in the past do not happen again (regression testing)
- Important note
  - *"Program testing can be used to show the presence of bugs, but never to show their absence!"* (Edsger W. Dijkstra)

Debugging

- Systematic approaches to fault localization + error removal
  - Testing output is often used to support debugging



* sometimes, also tests that do not trigger a failure but are similar to the failure-inducing ones

What is a test case?

- A test case is a set of inputs, execution conditions, and a pass/fail criterion
- Running a test case typically involves
  - Setup: bring the program to an **initial state** that fulfils the execution conditions
  - Execution: **run** the program on the actual inputs
  - Teardown: **record** the output, the final state, and any **failure** determined based on the pass/fail criterion
- A test set or test suite can include multiple test cases
- A test case specification is a requirement to be satisfied by one or more actual test cases
  - Example of test case specification: “*the input must be a sentence composed of at least two words*”
  - Example of test case input: “*this is a good test case input*”

Unit testing

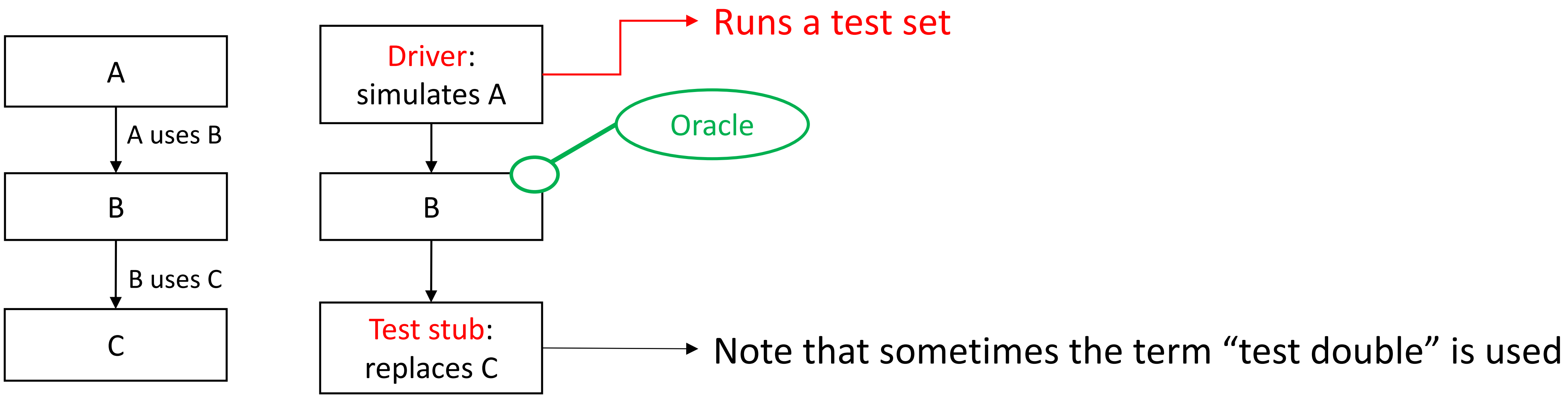
- Conducted by the developers
- Aimed at testing small pieces (units) of code in isolation
  - The notion of "unit" typically depends on the programming language (e.g., class, method, function, procedure)
- Why unit testing?
  - Find problems early

Coverage Report - All Packages

Package	# Classes	Line Coverage		Branch Coverage		Complexity
All Packages	221	84%	2970/3513	81%	859/1060	1.727
junit.extensions	6	82%	52/63	87%	7/8	1.25
junit.framework	17	76%	399/525	90%	139/154	1.605
junit.runner	3	49%	77/155	41%	23/56	2.225
junit.textui	2	76%	99/130	76%	23/30	1.686
org.junit	14	85%	196/230	75%	68/90	1.655
org.junit.experimental	2	91%	21/23	83%	5/6	1.5
org.junit.experimental.categories	5	100%	67/67	100%	44/44	3.357
org.junit.experimental.max	8	85%	92/108	86%	26/30	1.969
org.junit.experimental.results	6	92%	37/40	87%	7/8	1.222
org.junit.experimental.runners	1	100%	2/2	N/A	N/A	1

Unit testing and scaffolding

- The problem of testing in isolation: units may depend on other units
- We need to simulate missing units
  - e.g., we want to unit test B



Integration testing

- Aimed at exercising interfaces and components' interaction
- Faults discovered by integration testing
  - Inconsistent interpretation of parameters
    - e.g., mixed units (meters/yards) in Mars Climate Orbiter
  - Violations of assumptions about domains
    - e.g., buffer overflow
  - Side effects on parameters or resources
    - e.g., conflict on (unspecified) temporary file
  - Nonfunctional properties
    - e.g., unanticipated performance issues
  - Concurrency-specific problems (next lecture)

An example of integration error

- Apache web server, version 2.0.48
- Code fragment for reacting to normal Web page requests that arrived on the secure (https) server port
- Which problem do we have here?

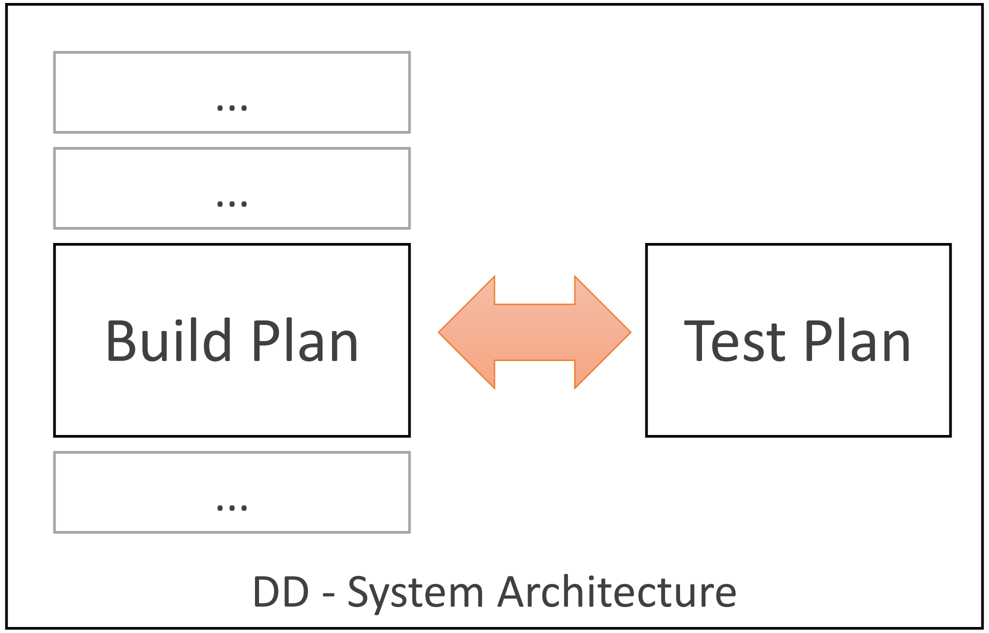
```
static void ssl_io_filter_disable(ap_filter_t *f) {
  bio_filter_in_ctx_t *inctx = f->ctx;

  inctx->ssl = NULL;
  inctx->filter_ctx->pssl = NULL;
}
```

An example of integration error

- Repair applied in version 2.0.49

```
static void ssl_io_filter_disable(SSLConnRec *sslconn, ap filter t *f) {
  bio_filter_in_ctx_t * inctx = f->ctx;
  SSL_free(inctx->ssl);
  sslconn->ssl = NULL;
  inctx->ssl = NULL;
  inctx->filter ctx->pssl = NULL;
}
```

Integration and test plan



- Typically defined by the Design Document
- Build plan = defines the order of the implementation
- Test plan = defines how to carry out integration testing
  - Must be consistent with the build plan!

Integration testing: strategies

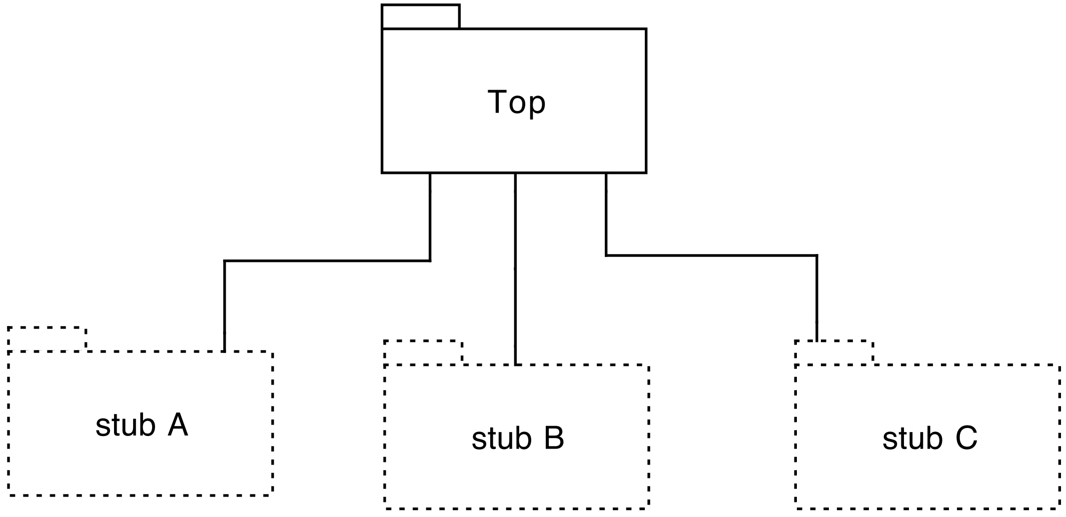
- Big bang: test only after integrating all modules together (not even a real strategy)
  - Pros
    - Does not require stubs, requires less drivers/oracles
  - Cons
    - Minimum observability, fault localization/diagnosability, efficacy, feedback
    - High cost of repair
      - Recall: Cost of repairing a fault increases as a function of time between the introduction of an error in the code and repair

Integration testing: strategies

- Iterative and incremental strategies
  - run as soon as components are released (not just at the end)
  - Hierarchical: based on the hierarchical structure of the system
    - Top-down
    - Bottom-up
  - Threads: a portion of several modules that offers a user-visible function
  - Critical modules

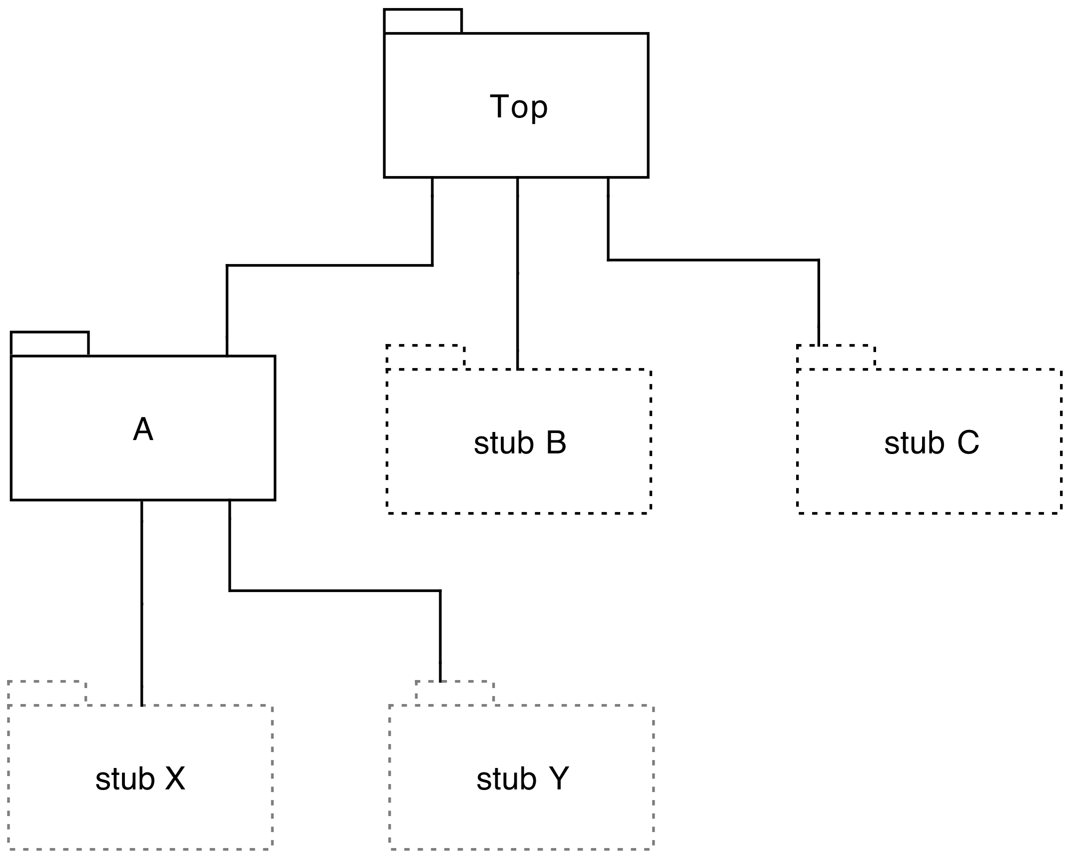
Integration testing: top-down

- Top-down strategy
  - Working from the top level (in terms of “use” or “include” relation) toward the bottom
  - Driver uses the top-level interfaces (e.g., CLI, REST APIs)
  - We need stubs of used modules at each step of the process



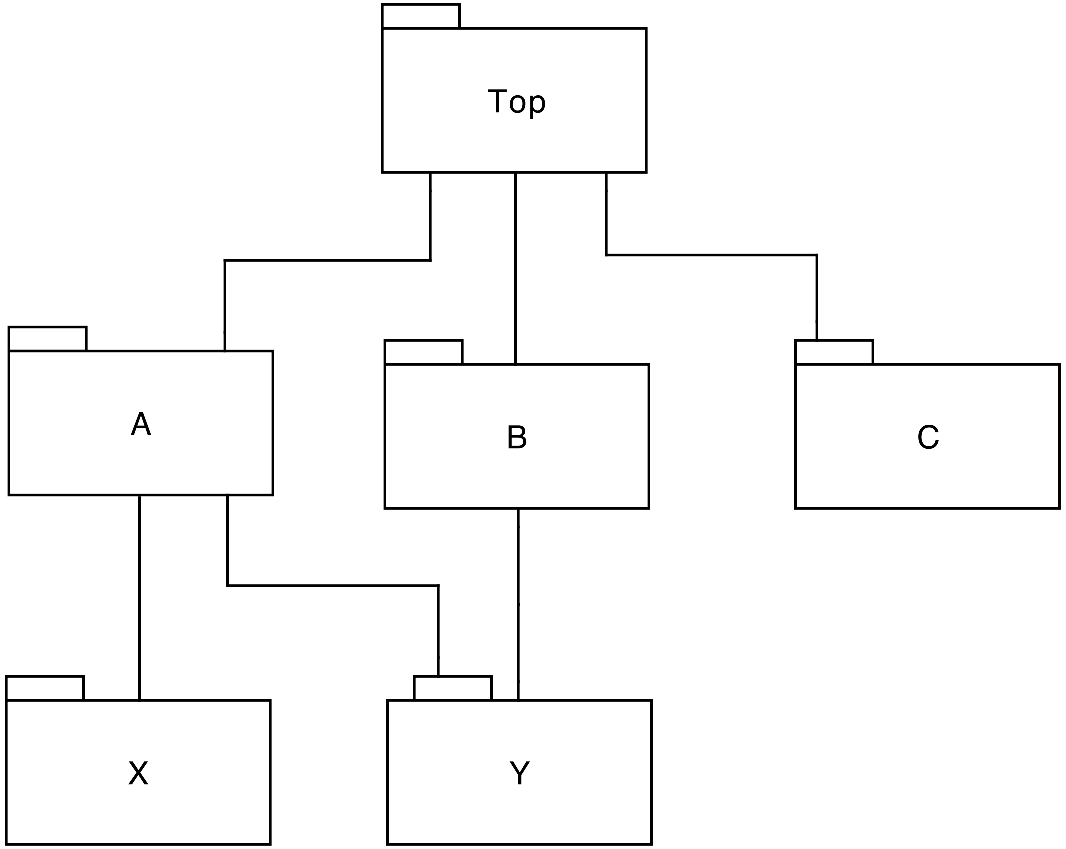
Integration testing: top-down

- Top-down strategy
  - As modules are ready (following the build plan) more functionality is testable
  - We replace some stubs and we need other stubs for lower levels



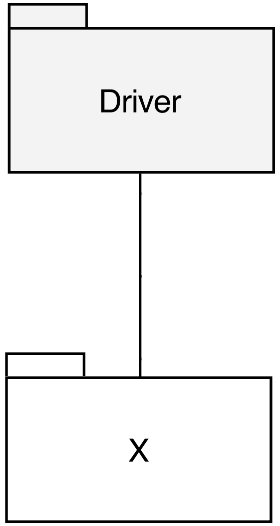
Integration testing: top-down

- Top-down strategy
  - When all modules are incorporated, the whole functionality can be tested



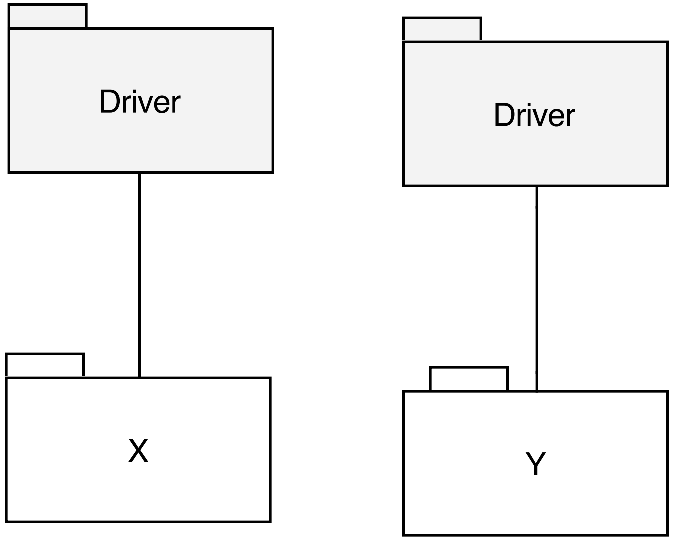
Integration testing: Bottom-up

- Bottom-up strategy
  - Starting from the leaves of the "uses" hierarchy
  - Does not need stubs



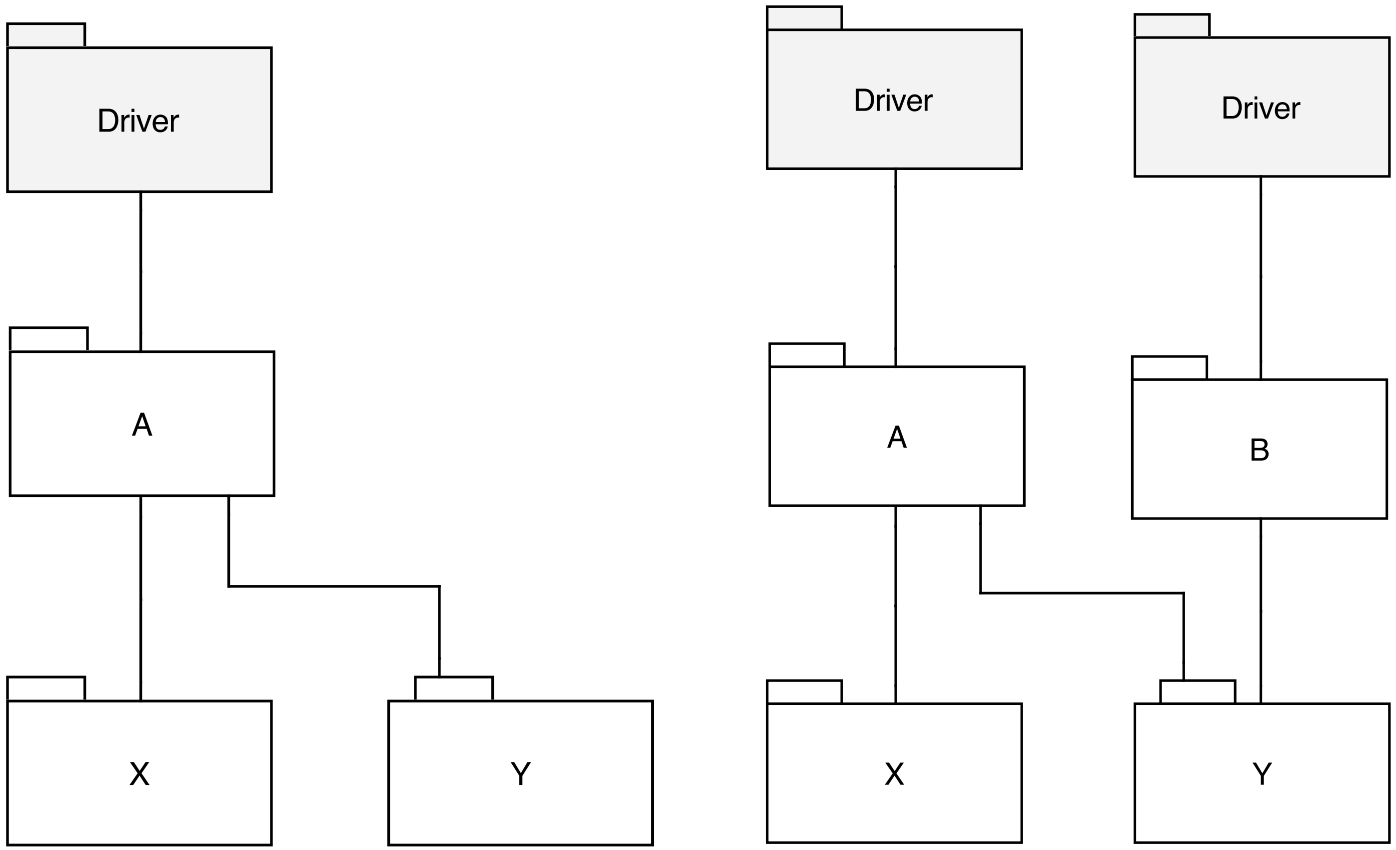
Integration testing: Bottom-up

- Bottom-up strategy
  - Starting from the leaves of the "uses" hierarchy
  - Does not need stubs
  - Typically requires more drivers: one for each module (as in unit testing)



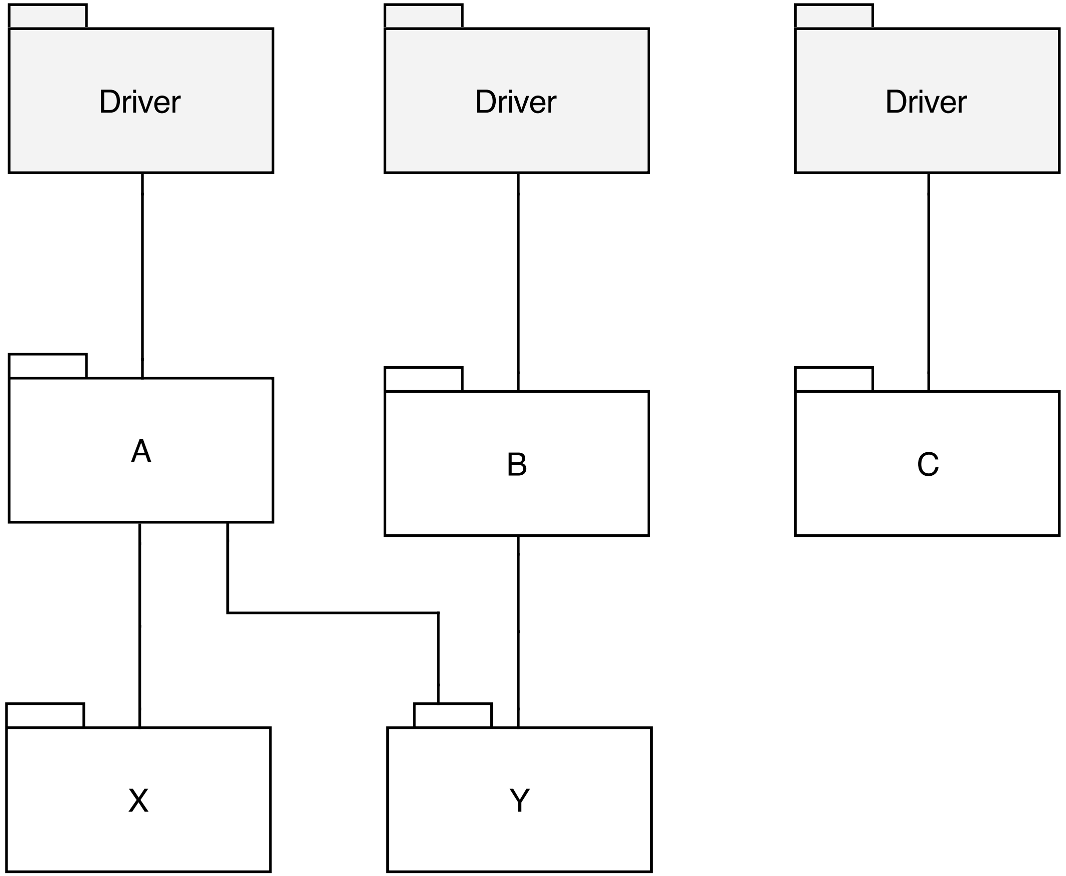
Integration testing: Bottom-up

- Bottom-up strategy
  - Newly developed module may replace an existing driver
  - New modules require new drivers



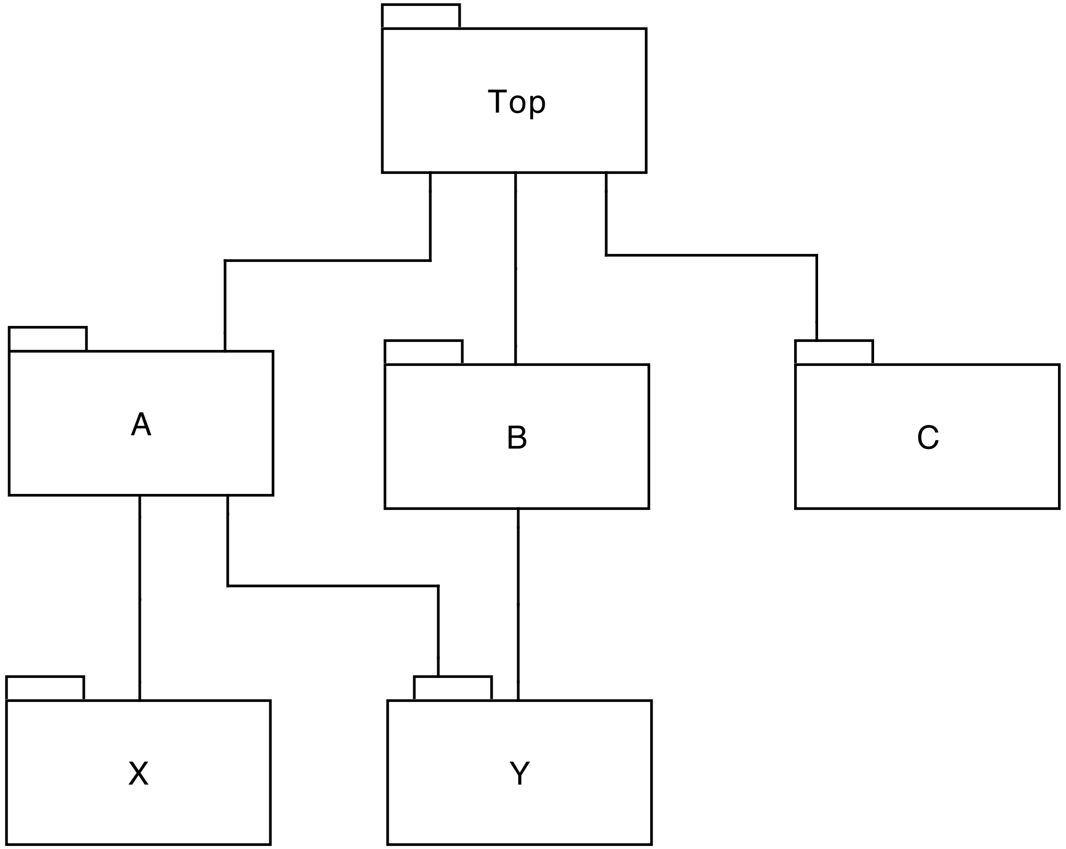
Integration testing: Bottom-up

- Bottom-up strategy
  - It may create several working subsystems



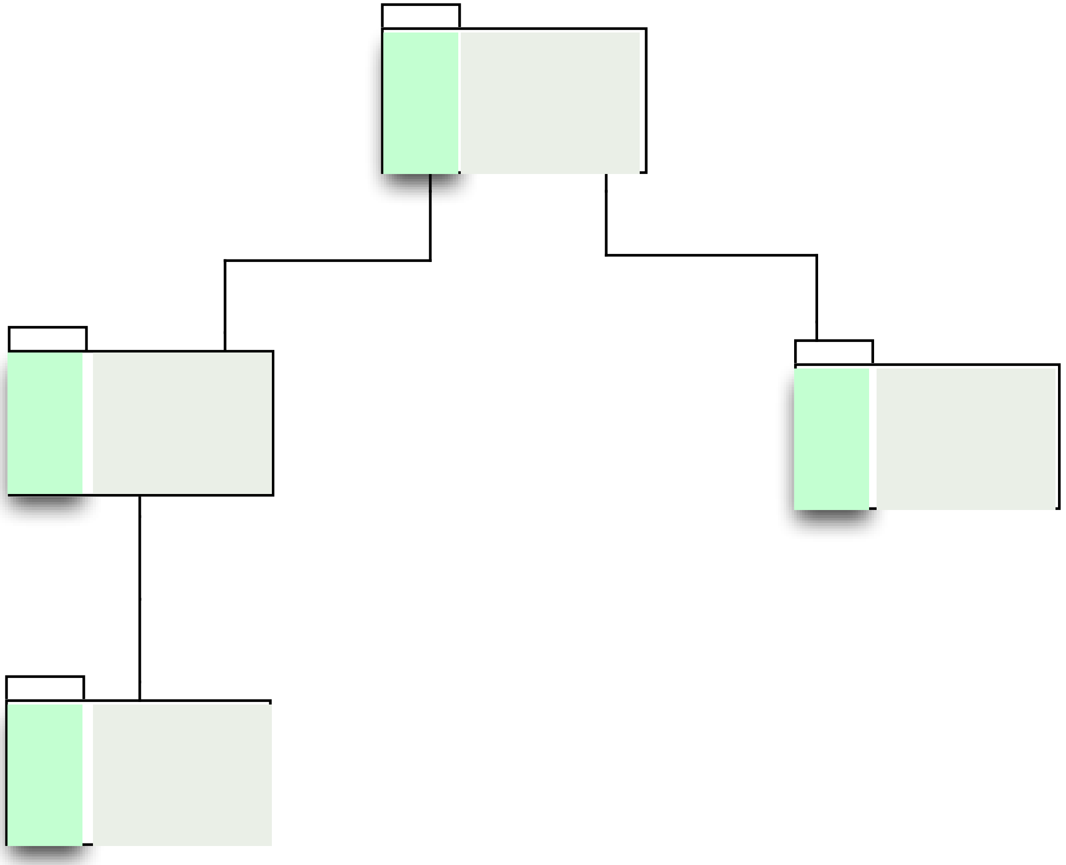
Integration testing: Bottom-up

- Bottom-up strategy
  - Working subsystems are eventually integrated into the final one



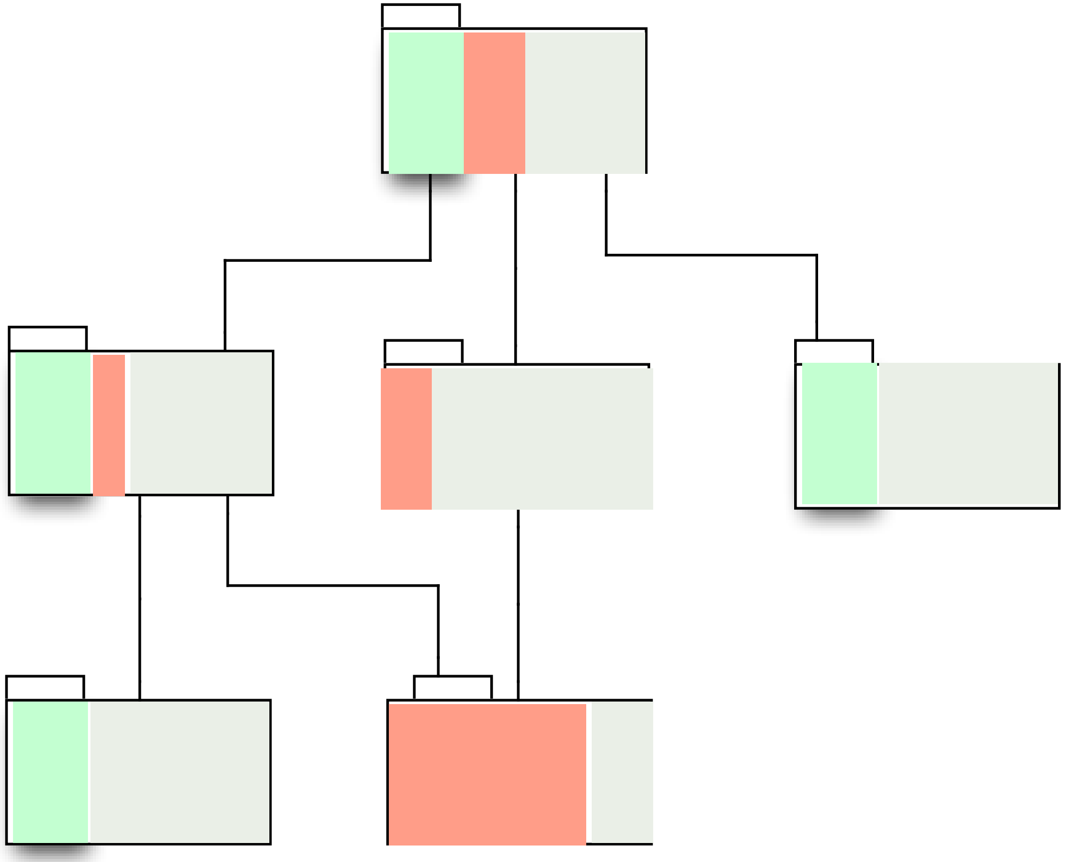
Integration testing: Threads

- Thread strategy
  - A thread is a portion of several modules that, together, provide a user-visible program feature



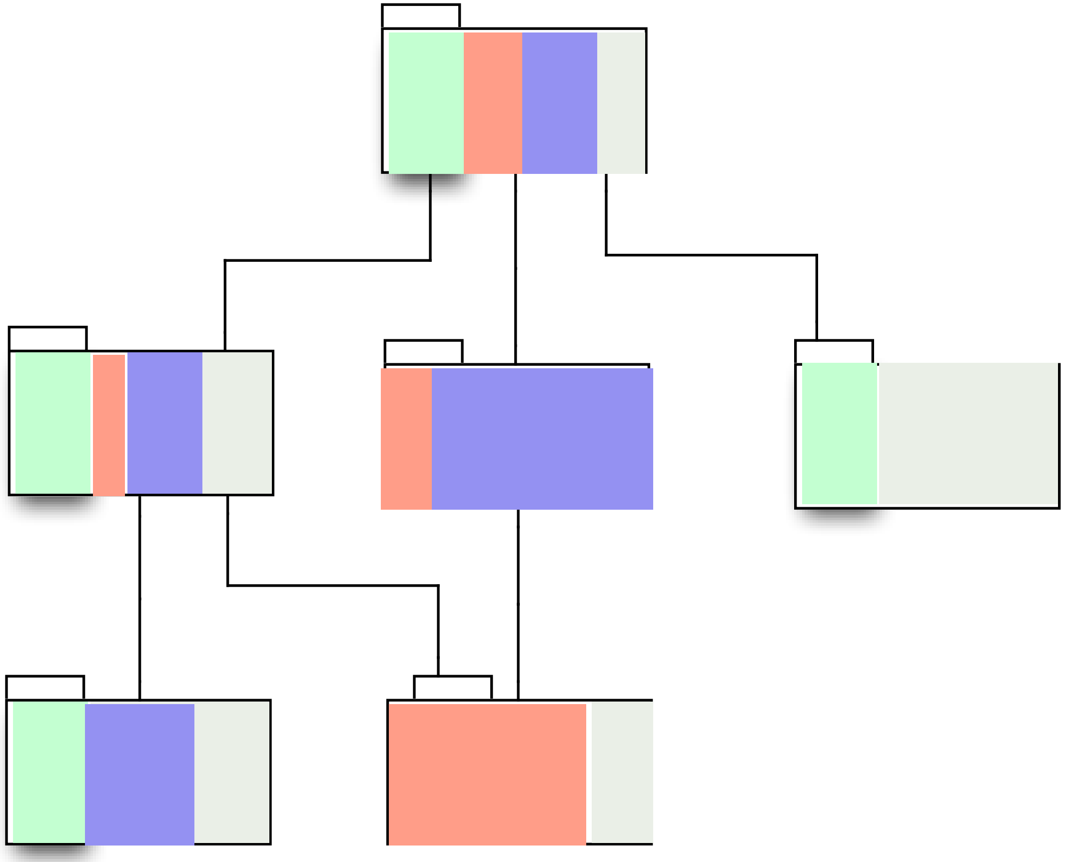
Integration testing: Threads

- Thread strategy
  - Integrating by thread maximizes visible progress for users (or other stakeholders)



Integration testing: Threads

- Thread strategy
  - Reduces drivers and stubs
  - Integration plan is typically more complex



Integration testing: critical modules

- Critical modules strategy
  - Start with modules having highest risk
    - Risk assessment is necessary first step
    - May include technical risks (is X feasible?), process risks (is schedule for X realistic?)
    - May resemble thread process with specific priority
  - Key point is risk-oriented process
    - Integration & testing as a risk-reduction activity, designed to deliver any bad news as early as possible

Integration testing: choosing a strategy

- Structural strategies (bottom up and top down) are simpler
- Thread and critical modules strategies provide better external visibility on progress (especially in complex systems)
- Possible to combine different strategies
  - Top-down and bottom-up are reasonable for relatively small components and subsystems
  - Combinations of thread and critical modules integration testing are often preferred for larger subsystems
  - Note: we can also combine threads and top-down/bottom-up

System (e2e) testing

- Conducted on a complete integrated system
- Independent teams (black box)
- Testing environment should be as close as possible to production environment
- Either functional or non-functional

System (e2e) testing: common types

- Functional testing
  - **Purpose**
    - Check whether the software meets the functional requirements
  - **How**
    - Use the software as described by use cases in the RASD, check whether requirements are fulfilled
- Performance testing
  - **Purpose**
    - Detect bottlenecks affecting response time, utilization, throughput
    - Detect inefficient algorithms
    - Detect hardware/network issues
    - Identify optimization possibilities
  - **How**
    - Load system with expected workload
    - Measure and compare acceptable performance

System (e2e) testing: common types

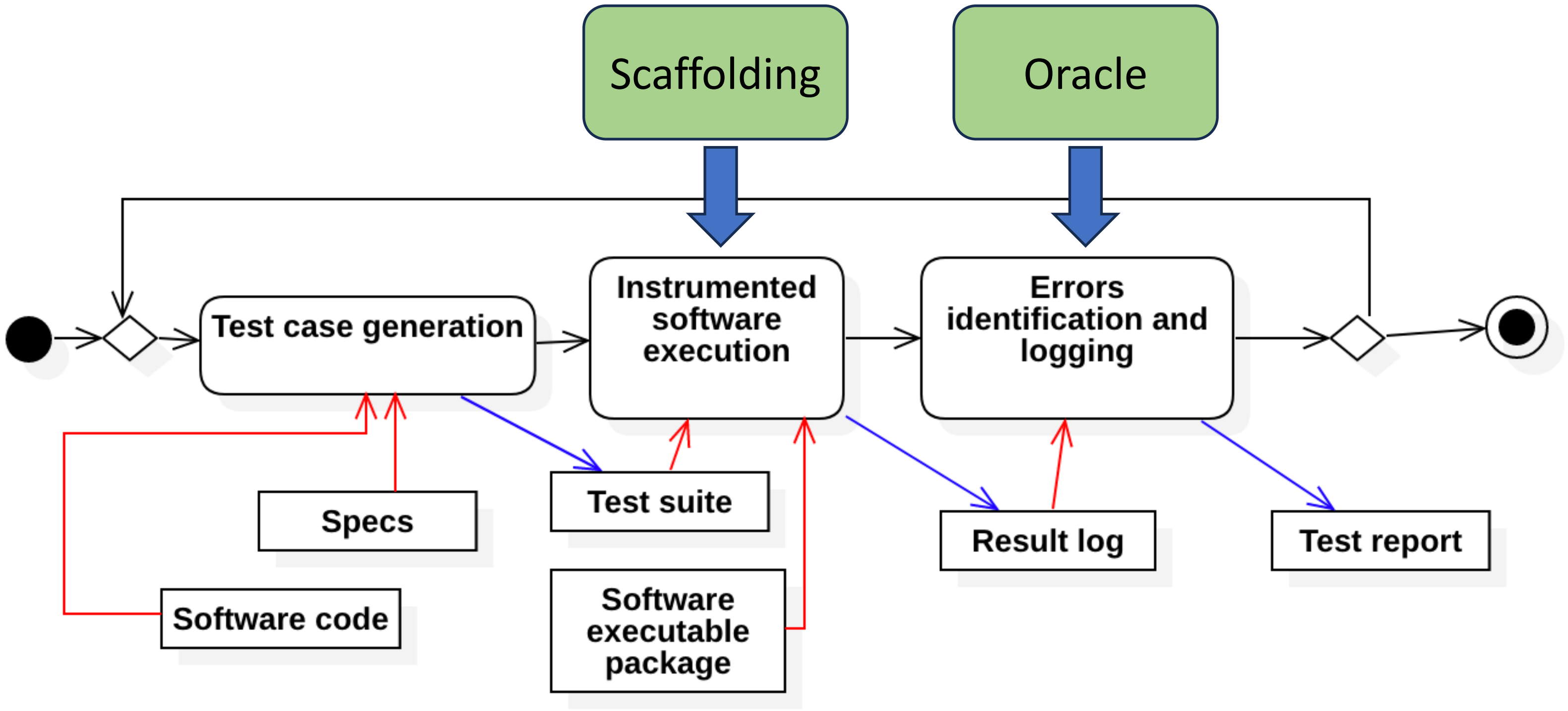
- Load testing
  - **Purpose**
    - Expose bugs such as memory leaks, mismanagement of memory, buffer overflows
    - Identify upper limits of components
    - Compare alternative architectural options
  - **How**
    - Test the system at increasing workload until it can support it
    - Load the system for a long period
  - Remember this piece of code?

```
static void ssl_io_filter_disable(ap_filter_t *f){
    bio_filter_in_ctx_t *inctx = f->ctx;
    inctx->ssl = NULL;
    inctx->filter_ctx->pssl = NULL;
}
```

System (e2e) testing: common types

- Stress testing
  - **Purpose**
    - Make sure that the system recovers gracefully after failure
  - **How**
    - Trying to break the system under test by overwhelming its resources or by reducing resources
  - **Examples**
    - Double the baseline number for concurrent users/HTTP connections
    - Randomly shut down and restart ports on the network switches/routers that connect servers
  - See also **Chaos engineering** (e.g., https://netflix.github.io/chaosmonkey/)

Testing workflow



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