ICS 221:
Software Analysis and Testing

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The Importance of “Testing”: the Ariane 501 explosion

On 4 June 1996, about 40 seconds after initiation of the flight sequence at an altitude of about 3700 m the launcher veered off its flight path, broke up and exploded.

The Inertial Reference System (IRS) computer, working on standby for guidance and attitude control, became inoperative. This was caused by an internal variable related to the horizontal velocity of the launcher exceeding a limit which existed in the software of this computer.

The backup IRS failed due to the same reason, so correct guidance and attitude information could no longer be obtained.

The limit was imposed according to the specification of the Ariane 4, when the software was ported to the Ariane 5 --whose flight specifications could exceed the imposed limit-- the specification was not changed and **no test** was performed using Ariane 5 actual trajectory data.

Why analysis and testing?

- Software is never correct no matter which developing technique is used
- Any software must be verified
- Software testing and analysis are
  - important to control the quality of the product (and of the process)
  - very (often too) expensive
  - difficult and stimulating

Testing vs. Analysis

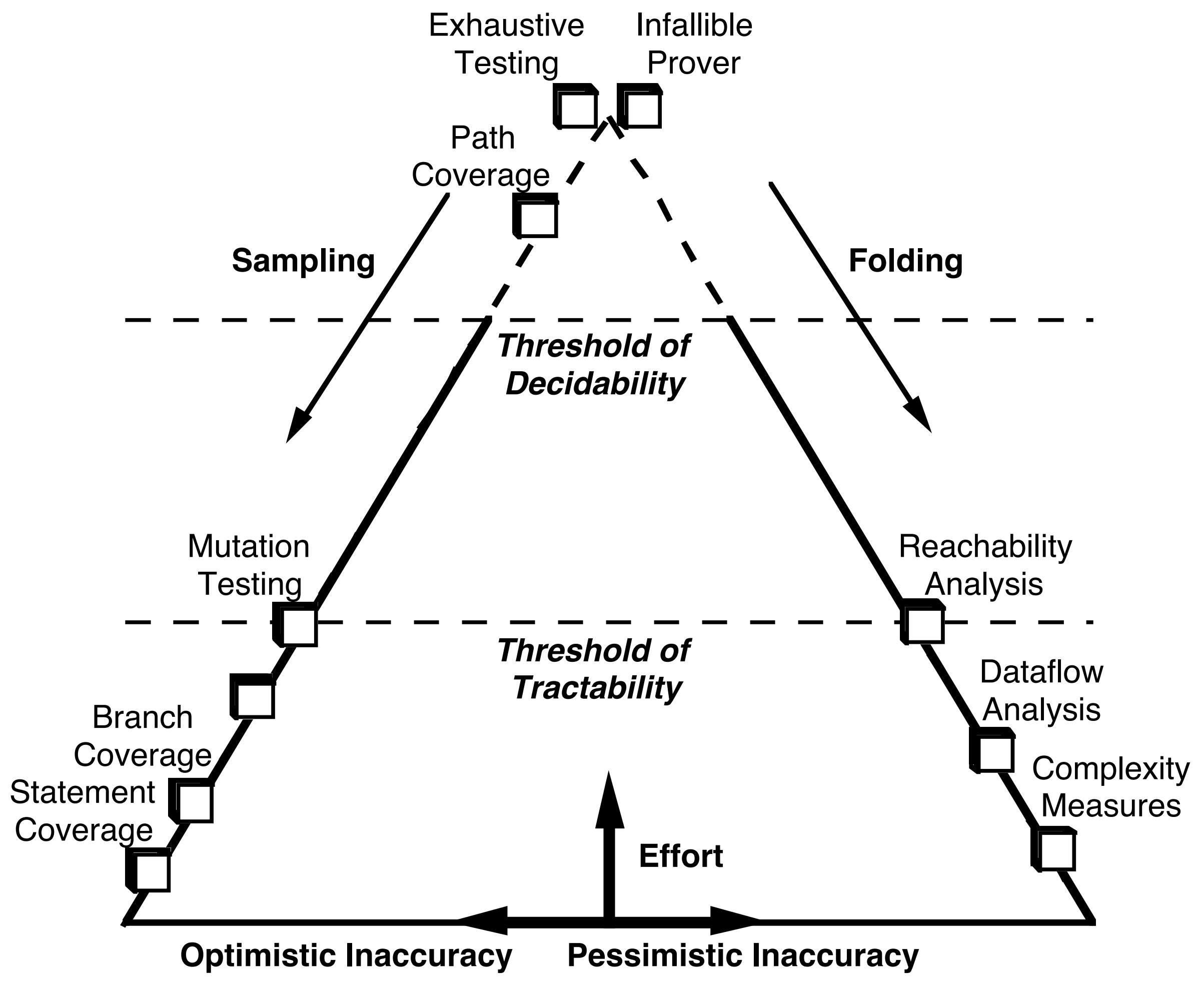
- Testing, as dynamic analysis, examines individual program executions
  - Results apply only to the executions examined
- In contrast, static analysis examines the text of the artifact under analysis
  - Proof of correctness, deadlock detection, safety/liveness/other property checking, etc.
  - Results apply to all possible executions

Problems with "Static/Dynamic"

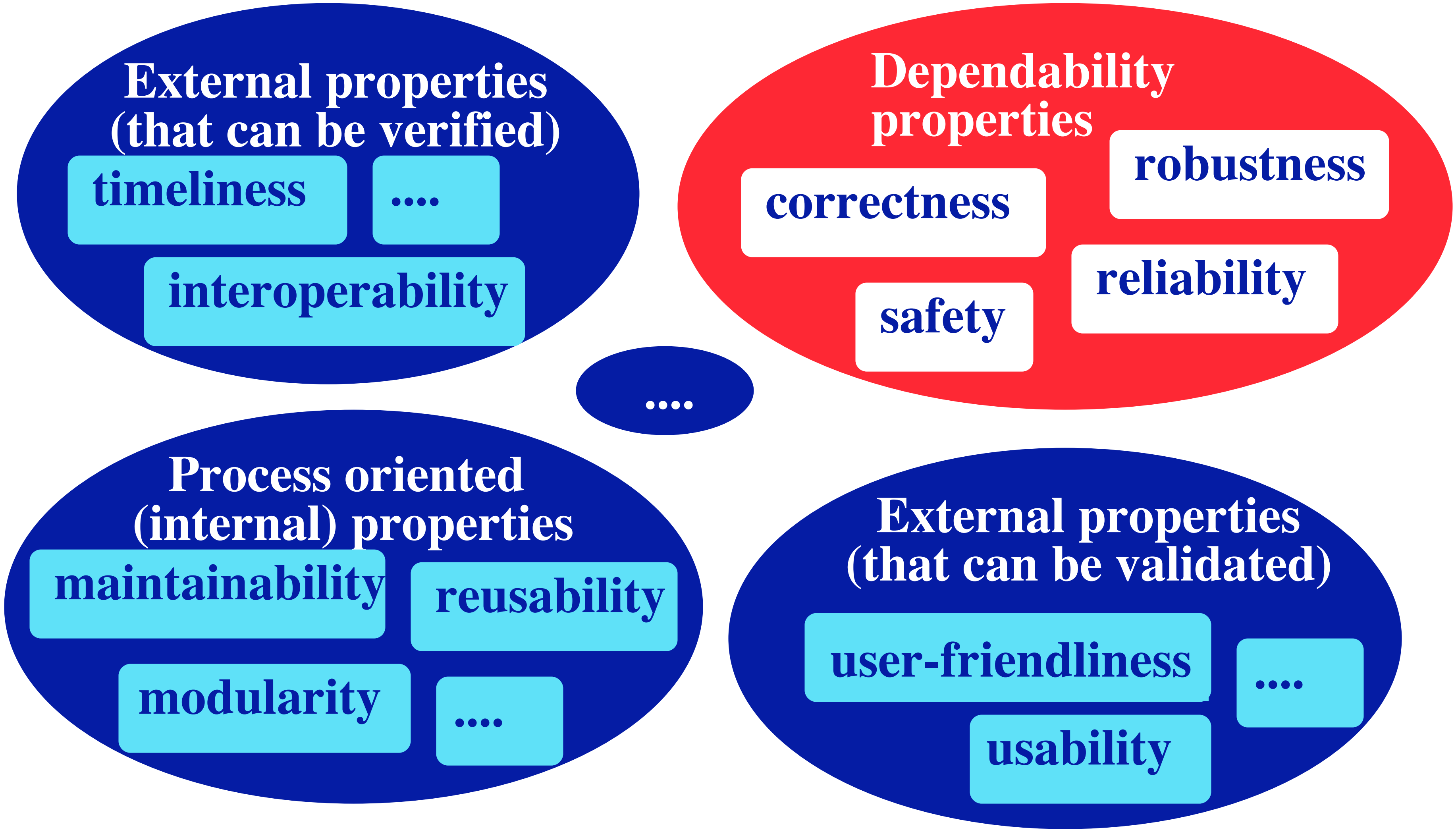
Young & Taylor, "Rethinking the Taxonomy of Fault Detection Techniques." *Proc. ICSE*, May 1989.

- Example: Model Checking
  - Evaluates individual executions/states
  - But is applied to all executions/states
- Example: Symbolic Execution
  - Examines source text
  - But summarizes individual executions/paths
- "Folding/Sampling" is a better discriminator

State-Space Exploration Pyramid



Software Qualities



External properties (that can be verified)

timeliness

....

interoperability

Dependability properties

robustness

correctness

reliability

safety

....

Process oriented (internal) properties

maintainability

reusability

modularity

....

External properties (that can be validated)

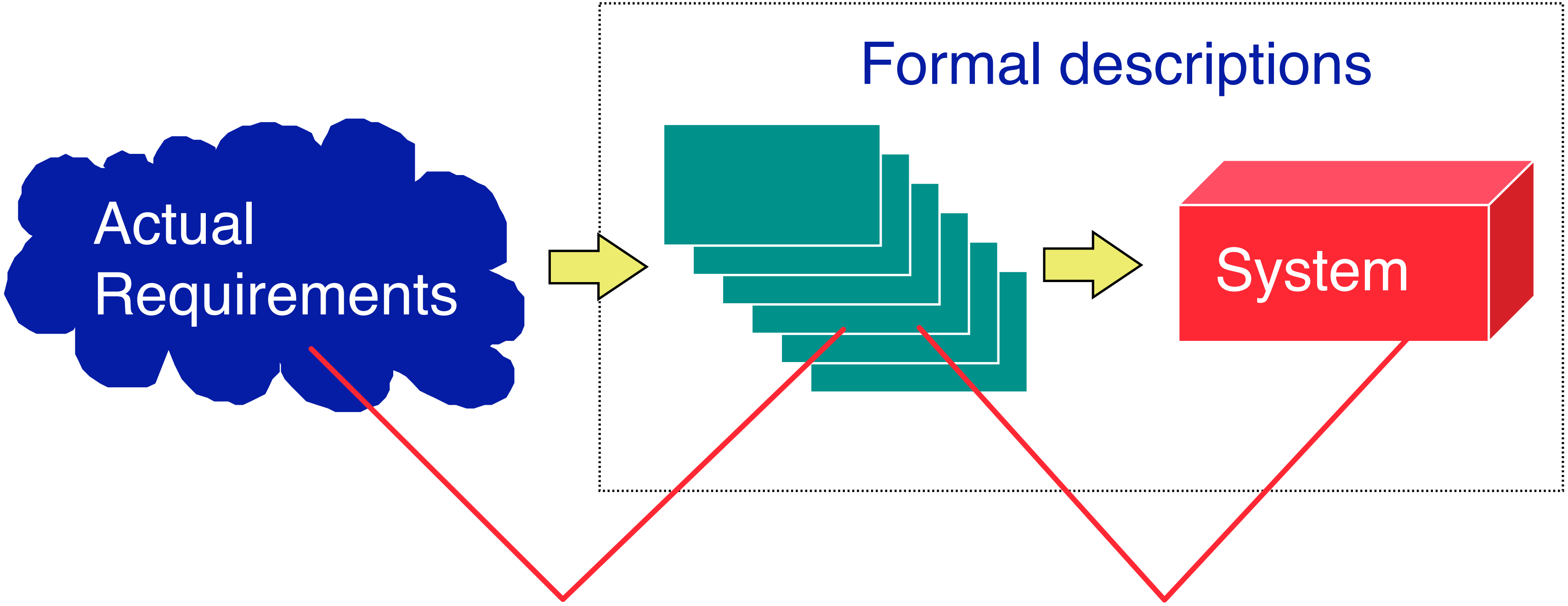
user-friendliness

....

usability

Validation vs. Verification

ABC, "Validation, Verification and Testing of Computer Software." *ACM Computing Surveys*, June 1982.



Formal descriptions

Actual Requirements

System

Validation

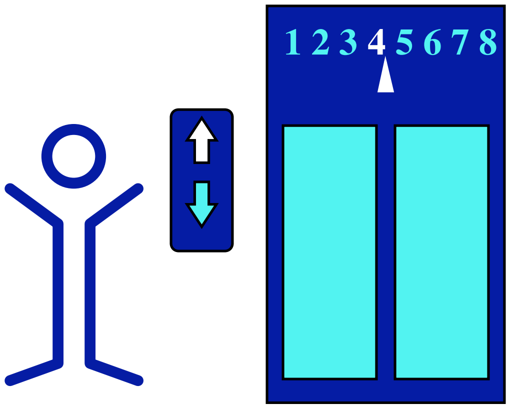
Includes usability testing, user feedback

Verification

Includes testing, inspections, static analysis

Verification or validation? depends on the property

Example: elevator response



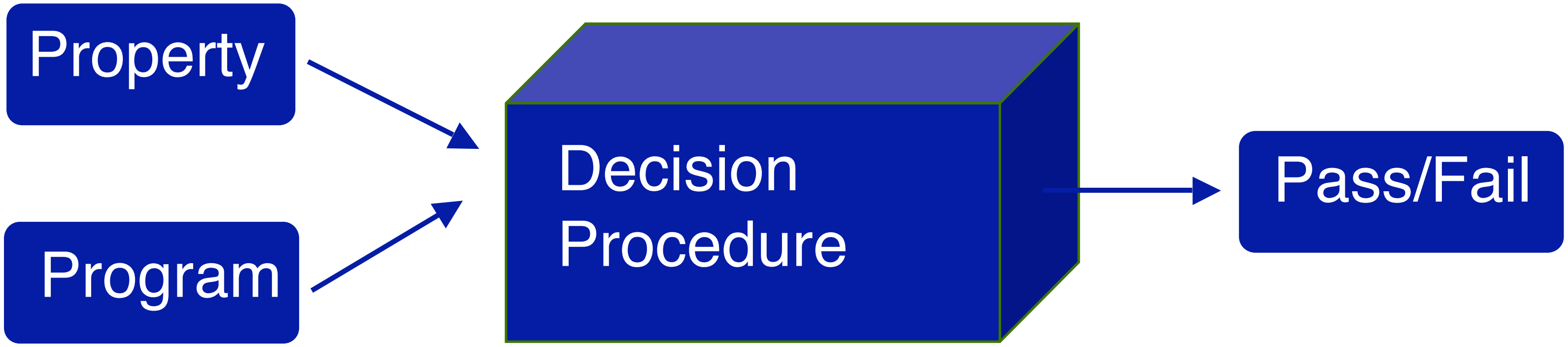
... if a user press a request button at floor i, an available elevator must arrive at floor i soon…

□ this property can be validated, but NOT verified (SOON is a subjective quantity)

... if a user press a request button at floor i, an available elevator must arrive at floor i within 30 seconds…

□ this property can be verified (30 seconds is a precise quantity)

You can't ~~always~~ *ever* get what you want

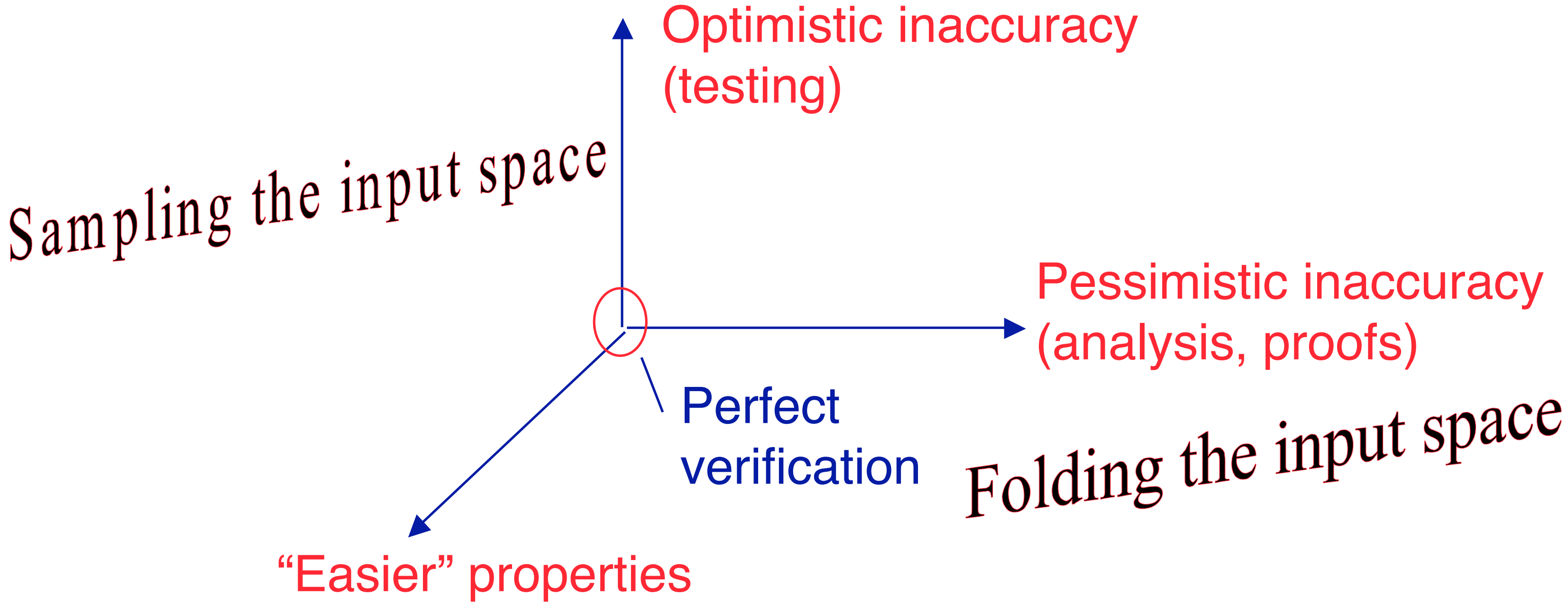


Correctness properties are undecidable

the halting problem can be embedded in almost every property of interest

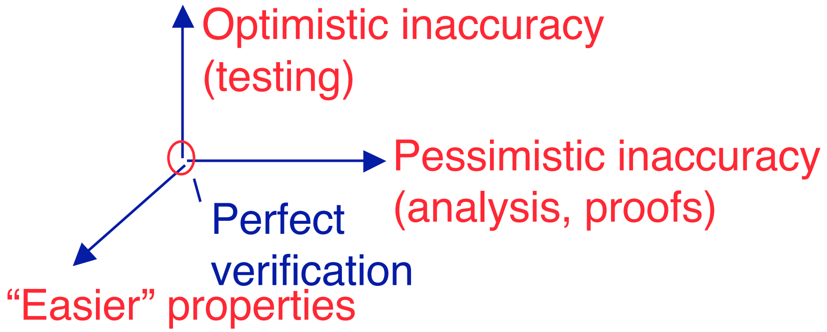
as close as possible to
Getting ∧ what you need ...

Young & Taylor, “Rethinking the Taxonomy of Fault Detection Techniques.” *Proc. ICSE*, May 1989.



We must make the problem of verification “easier” by permitting some kind of inaccuracy

The dimensions are not orthogonal



- Sufficient properties ~ pessimistic analysis
  - Analysis “false alarms” are in the area between desired property and checkable property
- Necessary properties ~ optimistic analysis
  - Faults go undetected if necessary conditions are satisfied

Impact of software on testing and analysis

- The type of software and its characteristics impact in different ways the testing and analysis activities:
  - different emphasis may be given to the same properties
  - different (new) properties may be required
  - different (new) testing and analysis techniques may be needed

Different emphasis on different properties

Dependability requirements

- they differ radically between
  - Safety-critical applications
    - flight control systems have strict safety requirements
    - telecommunication systems have strict robustness requirements
  - Mass-market products
    - dependability is less important than time to market
- can vary within the same class of products:
    - reliability and robustness are key issues for multi-user operating systems (e.g., UNIX) less important for single users operating systems (e.g., Windows or MacOS)

Different type of software may require different properties

- Timing properties
  - deadline satisfaction is a key issue for real time systems, but can be irrelevant for other systems
  - performance is important for many applications, but not the main issue for hard-real-time systems
- Synchronization properties
  - absence of deadlock is important for concurrent or distributed systems, not an issue for other systems
- External properties
  - user friendliness is an issue for GUI, irrelevant for embedded controllers

Different properties require different A&T techniques

- Performance can be analyzed using statistical techniques, but deadline satisfaction requires exact computation of execution times
- Reliability can be checked with statistical based testing techniques, correctness can be checked with test selection criteria based on structural coverage (to reveal failures) or weakest precondition computation (to prove the absence of faults)

Different A&T for checking the same properties for different software

- Test selection criteria based on structural coverage are different for
  - procedural software (statement, branch, path,…)
  - object oriented software (coverage of combination of polymorphic calls and dynamic bindings,…)
  - concurrent software (coverage of concurrent execution sequences,…)
  - mobile software (?)
- Absence of deadlock can be statically checked on some systems, require the construction of the reachability space for other systems

Principles

Principles underlying effective software testing and analysis techniques include:

- Sensitivity: better to fail every time than sometimes
- Redundancy: making intentions explicit
- Partitioning: divide and conquer
- Restriction: making the problem easier
- Feedback: tuning the development process

Sensitivity:
better to fail every time than sometimes

- Consistency helps:
  - a test selection criterion works better if every selected test provides the same result, i.e., if the program fails with one of the selected tests, it fails with all of them (reliable criteria)
  - run time deadlock analysis works better if it is machine independent, i.e., if the program deadlocks when analyzed on one machine, it deadlocks on every machine

Redundancy:

making intentions explicit

- Redundant checks can increase the capabilities of catching specific faults early or more efficiently.
  - Static type checking is redundant with respect to dynamic type checking, but it can reveal many type mismatches earlier and more efficiently.
  - Validation of requirements is redundant with respect to validation of final software, but can reveal errors earlier and more efficiently.
  - Testing and proof of properties are redundant, but are often used together to increase confidence

Partitioned:

divide and conquer

- Hard testing and verification problems can be handled by suitably partitioning the input space:
  - both structural and functional test selection criteria identify suitable partitions of code or specifications (partitions drive the sampling of the input space)
  - verification techniques fold the input space according to specific characteristics, thus grouping homogeneous data together and determining partitions

Restriction:
making the problem easier

- Suitable restrictions can reduce hard (unsolvable) problems to simpler (solvable) problems
  - A weaker spec may be easier to check: it is impossible (in general) to show that pointers are used correctly, but the simple Java requirement that pointers are initialized before use is simple to enforce.
  - A stronger spec may be easier to check: it is impossible (in general) to show that type errors do not occur at run-time in a dynamically typed language, but statically typed languages impose stronger restrictions that are easily checkable.

Feedback:
tuning the process

- Learning from experience:
  - checklists are built on the basis of errors revealed in the past
  - error taxonomies can help in building better test selection criteria

Goals of Testing

- Find faults ("Debug" Testing):

  a test is successful if the program fails

- Provide confidence (Acceptance Testing)
  - of reliability
  - of (probable) correctness
  - of detection (therefore absence) of particular faults

Goals of Analysis

- Formal proof of software properties
  - restrict properties (“easier” properties) or programs (“structured” programs) to allow algorithmic proof
    - data flow analysis
    - necessary □sufficient conditions
  - compromise between
    - accuracy of the property
    - generality of the program to analyze
    - complexity of the analysis
    - accuracy of the result

Analysis and Testing are Creative

- Testing and analysis are important, difficult, and stimulating
  - Good testing requires as much skill and creativity as good design, because testing *is* design
- Testers should be chosen from the most talented employees
  - It is a competitive advantage to produce a high-quality product at acceptable, predictable cost
- Design the product and process for test
  - The process: for visibility, improvement
  - The product: for testability at every stage

Fundamental “Testing” Questions

- Test Adequacy Metrics:
  How much to test?
- Test Selection Criteria:
  What should we test?
- Test Oracles:
  Is the test correct?

How to make the most of limited resources?

Test Adequacy Metrics

- Theoretical notions of test adequacy are usually defined in terms of adequacy metrics/measures
  - Coverage metrics
  - Empirical assurance
  - Error seeding
  - Independent testing
- Adequacy criteria are evaluated with respect to a test suite and a program under test
- The program under test is viewed in isolation

Test Selection Criteria

- Testing must select a subset of test cases that are likely to reveal failures
- Test Criteria provide the guidelines, rules, strategy by which test cases are selected
  - requirements on test data -> conditions on test data -> actual test data
- Equivalence partitioning
  - a test of any value in a given class is equivalent to a test of any other value in that class
  - if a test case in a class reveals a failure, then any other test case in that class should reveal it
  - some approaches limit conclusions to some chosen class of faults and/or failures

Test Oracles/Correctness

- A test oracle is a mechanism for verifying the correct behavior of test execution
  - extremely costly and error prone to verify
  - oracle design is a critical part of test planning
- Sources of oracles
  - input/outcome oracle
  - tester decision
  - regression test suites
  - standardized test suites and oracles
  - gold or existing program
  - formal specification

Theory of Test Adequacy

Goodenough & Gerhart, “Toward a Theory of Test Data Selection.” *IEEE TSE*, Jan 1985.

Let

P	*= program under test*
S	*= specification of P*
D	*= input domain of S and P*
T	*= subset of D, used as test set for P*
C	*= test adequacy criterion*

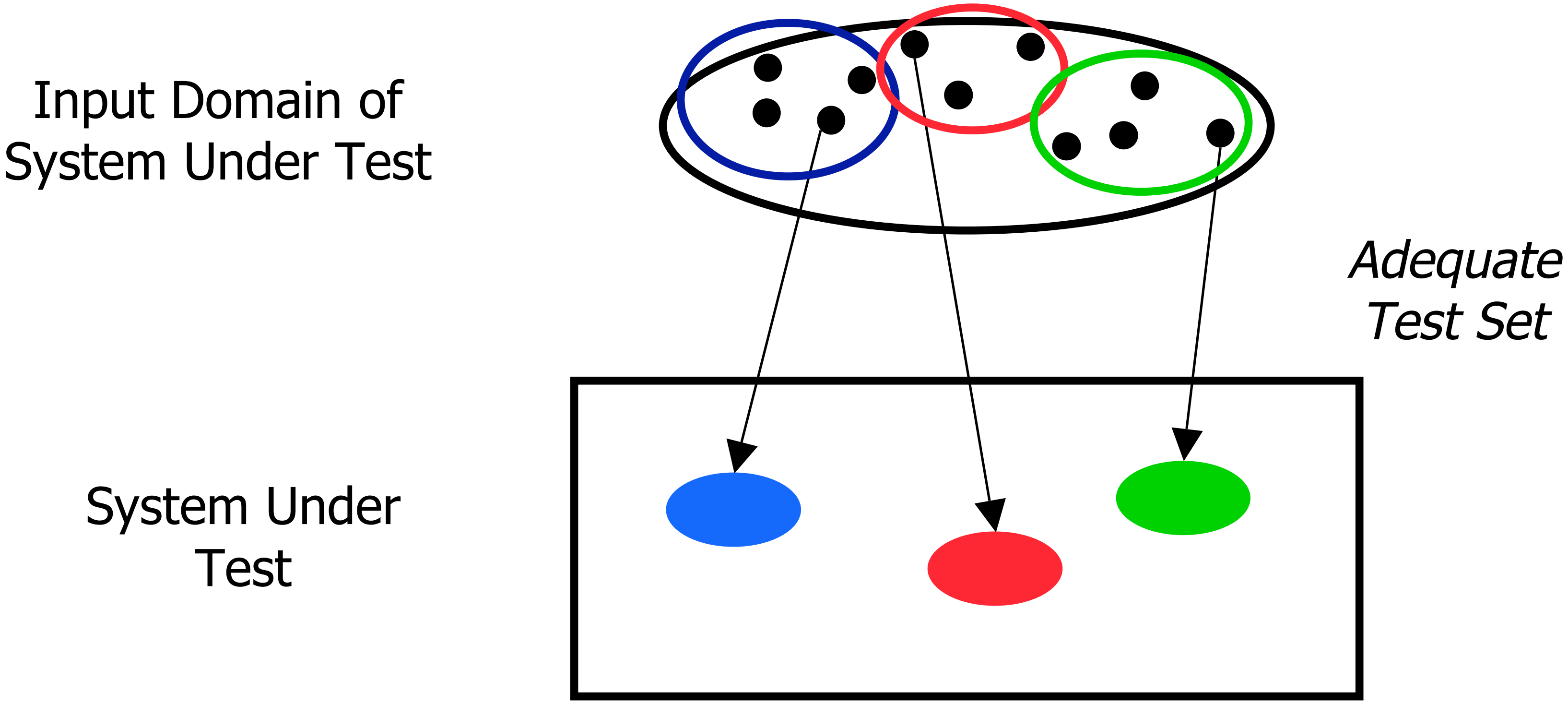
- P is incorrect if it is *inconsistent* with S on some element of D
- T is unsuccessful if there exists an element of T on which P is *incorrect*

Subdomain-Based Test Adequacy

- A test adequacy criterion C is subdomain-based if it induces one or more subsets, or subdomains, of the input domain D

- A subdomain-based criterion C typically does not partition D (into a set of non-overlapping subdomains whose union is D)

An Example: Statement Coverage



Test adequacy Axioms

Elaine Weyuker, “Axiomatizing Software Test Data Adequacy” *IEEE TSE*, Dec 1986.

- Applicability
  - For every P, there is a finite adequate T
- Nonexhaustive applicability
  - For at least one P, there is a non-exhaustive adequate T
- Monotonicity
  - If T is adequate for P and T ⊆ T′, then T′ is adequate for P
- Inadequate Empty Set
  - The empty set is not adequate for any P

Test Adequacy Axioms (cont.)

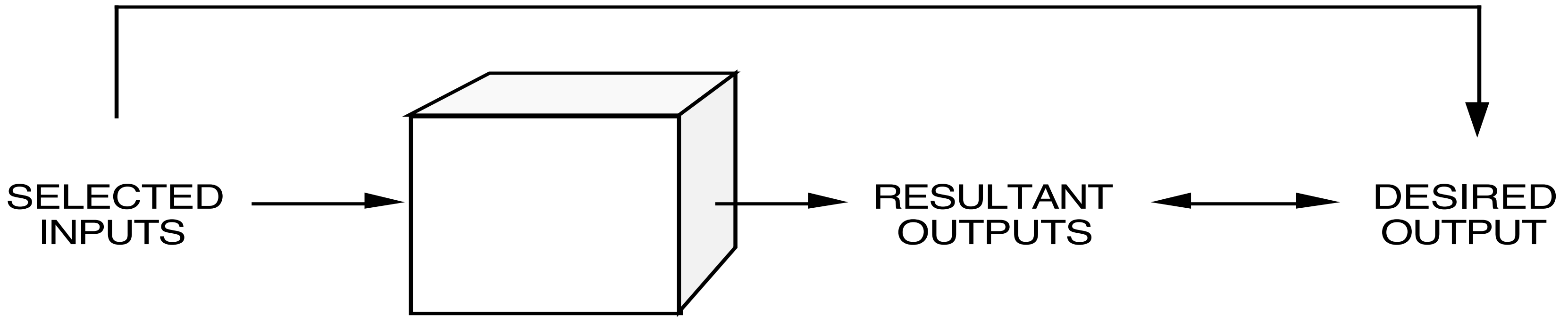
- Anti-extensionality
  - There are programs P1 and P2 such that P1 ° P2 and T is adequate for P1 but not P2
- General Multiple Change
  - There are programs P1 and P2 such that P2 can be transformed into P1 and T is adequate for P1 but not P2
- Anti-decomposition
  - There is program P with component Q such that T is adequate for P, but the subset of T that tests Q is not adequate for Q
- Anti-composition
  - There are programs P1 and P2 such that T is adequate for P1 and P1(T) is adequate for P2 but T is not adequate for P1;P2

Functional and Structural Test Selection Criteria

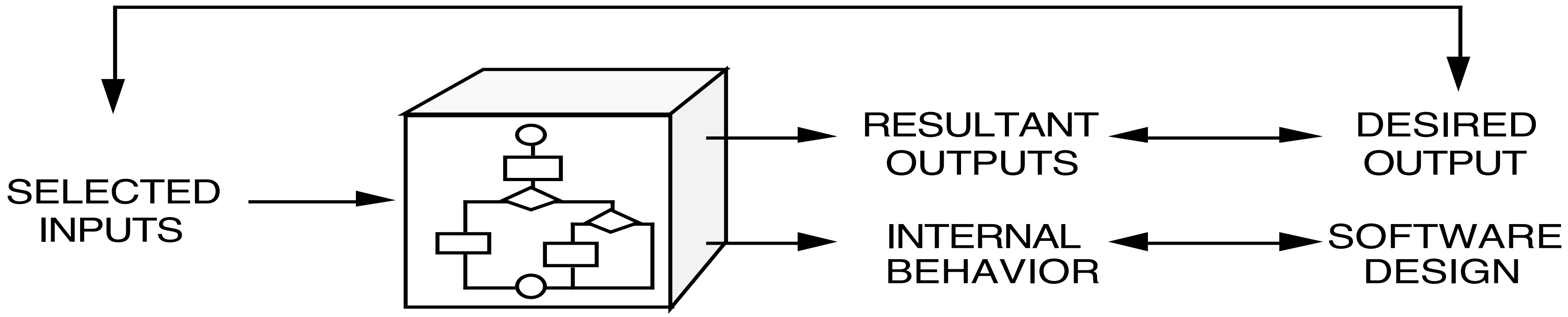
- Functional Testing
  - Test cases selected based on specification
  - Views program/component as *black box*
- Structural Testing
  - Test cases selected based on structure of code
  - Views program /component as *white box* (also called *glass box* testing)

*Can do black-box testing of **program** by doing white-box testing of **specification***

Black Box vs. White Box Testing



“BLACK BOX” TESTING



“WHITE BOX” TESTING

Structural (White-Box) Test Criteria

- Criteria based on
  - control flow
  - data flow
  - expected faults
- Defined formally in terms of flow graphs
- Metric: percentage of coverage achieved
- Adequacy based on metric requirements for criteria

Objective: ***Cover*** *the software structure*

Flow Graphs

- Control Flow
  - The partial order of statement execution, as defined by the semantics of the language
- Data Flow
  - The flow of values from definitions of a variable to its uses

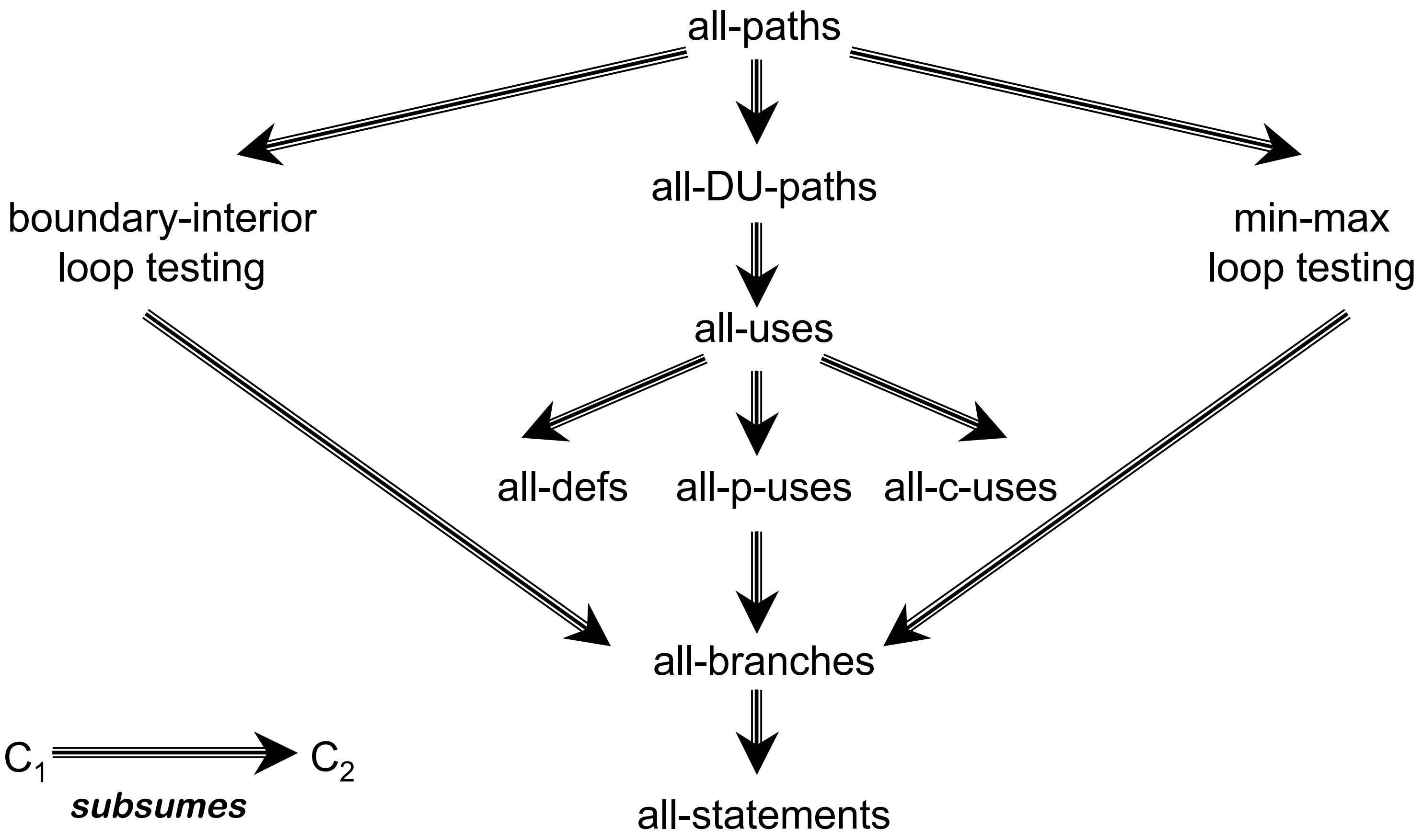
Graph representation of control flow and data flow relationships

Subsumption and Covers

- C1 *subsumes* C2 if any C1-adequate T is also C2-adequate
  - But some T1 satisfying C1 may detect fewer faults than some T2 satisfying C2
- C1 *properly covers* C2 if each subdomain induced by C2 is a union of subdomains induced by C1

Structural Subsumption Hierarchy

Clarke, Podgurski, Richardson, and Zeil, “A Formal Evaluation of Data Flow Path Selection Criteria”, *IEEE TSE*, Nov 1989.



all-paths

boundary-interior loop testing

all-DU-paths

min-max loop testing

all-uses

all-defs

all-p-uses

all-c-uses

all-branches

all-statements

C_1 C_2

subsumes

What makes a program Testable?

Elaine Weyuker, “On Testing Nontestable Programs” *Computer Journal,* Nov 1982.

- Testing assumes existence of a test oracle
- Program is non-testable if it requires extra-ordinary effort to determine test correctness
  - Often the case

D.J. Richardson, S.L. Aha, and O.O’Malley, “Specification-based Test Oracles…”, *ICSE-14*, May 1992.

- One solution: specification-based test oracles
  - Derive a test oracle from a specification
    - Possibly only for critical properties
    - Another argument for specification-based testing

Why Specification-based A&T?

J. Chang and D.J. Richardson, “Structural Specification-based Testing…”, ESEC/ FSE’99, Sept 1999.

D.J. Richardson, O.O’Malley, and C. Tittle, “Approaches to Specification-based Testing”, *TAV-3,* Dec 1989.

- Specification states what system should do
  - this information should be used to drive testing
  - code-based testing detects errors of omission only by chance
  - specification-based testing is more likely to detect errors of omission
- Specifications enable formalized automation
- Specification-based analysis and testing should augment code-based testing

To detect, diagnose, and eliminate defects as efficiently and early as possible

Why Software Architecture-based A&T?

- SA-based A&T supports architecture-based and component-based software development
- Software Quality Assurance:
  - quality of the components and of their configurations
  - analysis in the context of connections and interactions between components
- Architecture Level of Abstraction:
  - components, connectors and configurations are better understood and intellectually tractable
  - analysis may address both behavioral and structural qualities, such as functional correctness, timing, performance, style, portability, maintainability, etc

Analysis at a higher level of abstraction makes the problem less complex

Specification-based Testing Applied to Software Architecture

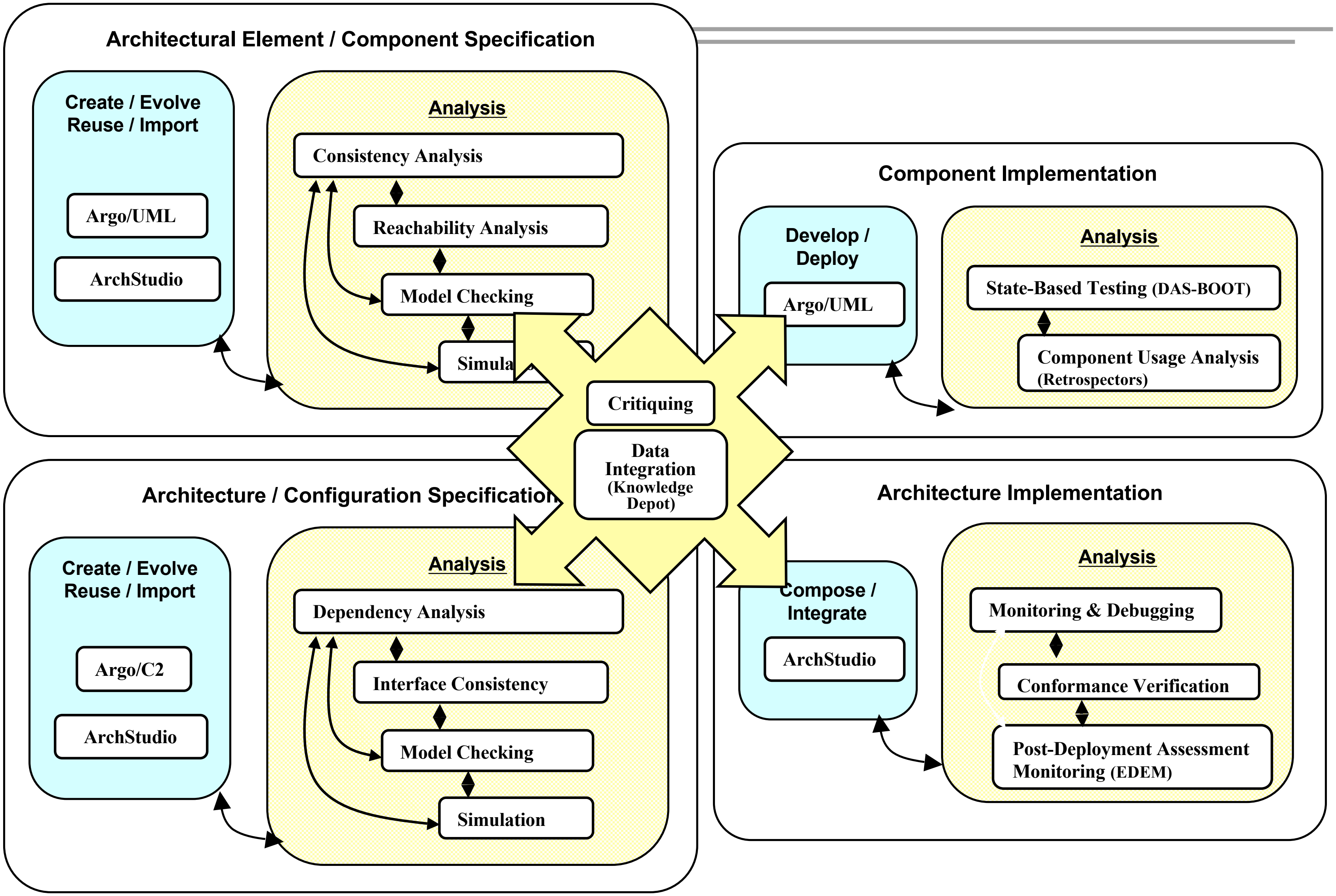
- During Requirements
  - specify critical system behaviors requiring highest assurance
- Architecture-based Testing
  - test structure for conformance to architectural design
  - test system and/or components against specified properties
- Component-based Testing
  - test components without knowing where they will be used
  - test component-based system consisting of OTS components
- Operational testing
  - monitoring of deployed software to perpetually verify behavior against residual test oracles and assumptions made during development-time analysis and testing

Argus-I: All-Seeing Architecture-based Analysis

M. Vieira, M. Dias, D.J. Richardson, "Analyzing Software Architectures with Argus-I", ICSE 2000, June 2000.

- Iterative, evolvable analysis during architecture specification and implementation
- Specification-based architecture analysis
  - structural and behavioral analysis
  - component and architecture levels
  - static and dynamic techniques
- Current version
  - architectures in the C2-style (structure specification)
  - component behavior specification described by statecharts
- Future versions
  - generalize to other architectural styles and ADLs

Coordinated Architectural Design and Analysis with Argus-I



Selected Current Work

M. Vieira, D.J. Richardson, “Analyzing Dependencies in Large Component-Based Systems”, ASE 2002, Sept 2002.

- Component-Based Dependence Analysis
  - Static Analysis
  - Based on Architecture Specification and Component Implementation
  - For testing, maintenance and evolution

M. Dias, D.J. Richardson,” Architecting Dependable Systems with xMonEve, an extensible event description language for monitoring”, ICSSEA 2002), Dec 2002.

- Software Architecture Monitoring
  - Dynamic Analysis
  - Based on Architecture Specification and Implementation
  - For performance, conformance checking, understanding and visualization