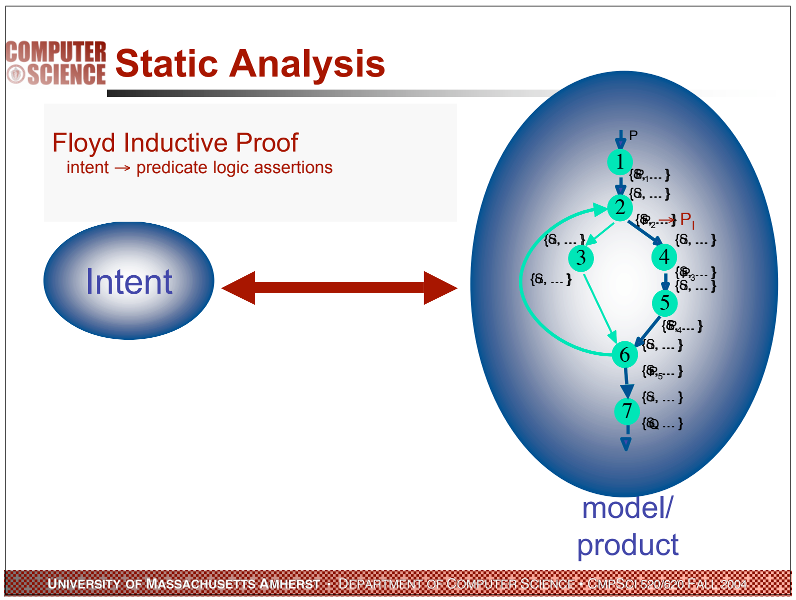
23-Analysis Overview

- Readings:
  - GJM03 Chapter 6
  - Adr82 Adrion, W.R,. M.A. Branstad, and J.C. Cherniavsky, "Validation, Verification and Testing of Computer Software," ACM Computing Surveys, June 1982, pp.159--192
  - Hoa69 Hoare, C.A.R., "An Axiomatic Basis for Computer Programming," Communications of the ACM, October 1969.
  - Flo67 Floyd, R.W. "Assigning Meaning to Programs", in the Proceedings of Symposium on Applied Mathematics, 1967, pp. 19-32, (Appeared as volume 19 of Mathematical Aspects of Computer Science).
  - Han76 Hantler, S.L. and J.C King,. "An Introduction to Proving the Correctness of Programs," ACM Computing Surveys, September 1976, pp. 278-300.
  - Cla85 Clarke L. A. and D. J. Richardson, "Applications of Symbolic Evaluation," Journal of Systems and Software, January 1985, 5 (1), pp.15-35.
  - Zhu97 Zhu, Hong, Patrick A. V. Hall, and John H. R. May, "Software Unit Test Coverage and Adequacy," ACM Computing Surveys, vol. 29, no.4, pp. 366-427, December, 1997.
  - Wey80 Weyuker, Elaine J. and Thomas Ostrand, "Theories of Program Testing and the Application of Revealing Subdomains," IEEE Transactions on Software Engineering, May 1980, SE-6(5), pp. 236-246
  - DeM79 DeMillo R.A. and R.J. Lipton and A.J. Perlis, "Social Processes and Proofs of Theorems and Programs, Communications of the ACM, May 1979, 22(5), pp. 271-280

Approaches

- Static Analysis
  - Inspections
  - Software metrics
  - Symbolic execution
  - Dependence Analysis
  - Data flow analysis
  - Software Verification
- Dynamic Analysis
  - Assertions
  - Error seeding, mutation testing
  - Coverage criteria
  - Fault-based testing
  - Specification-based testing
  - Object-oriented testing
  - Regression testing


COMPUTER SCIENCE
Static Analysis
Floyd Inductive Proof
intent → predicate logic assertions
Intent
P
1
2
3
4
5
6
7
model/
product
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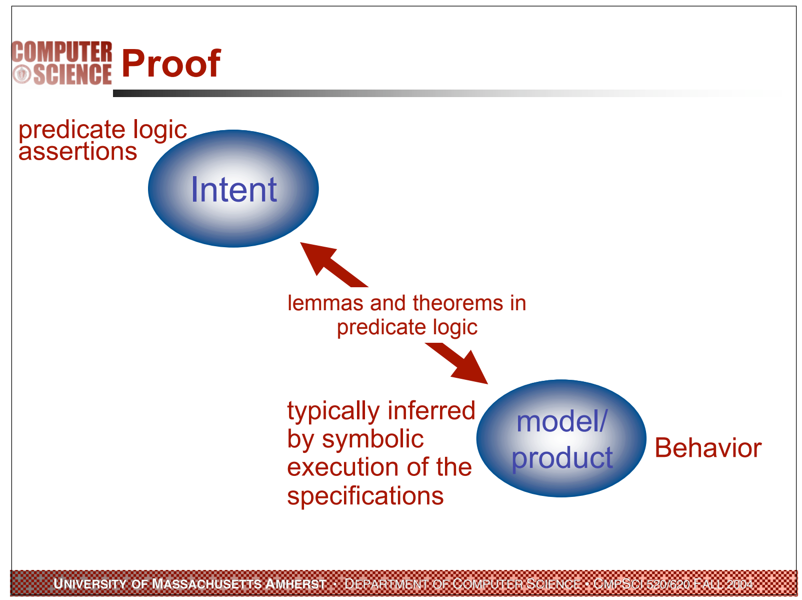
COMPUTER SCIENCE
Proof
predicate logic assertions
Intent
lemmas and theorems in predicate logic
typically inferred by symbolic execution of the specifications
model/
product
Behavior
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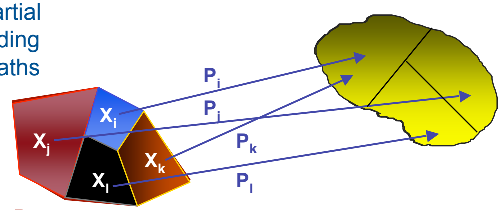
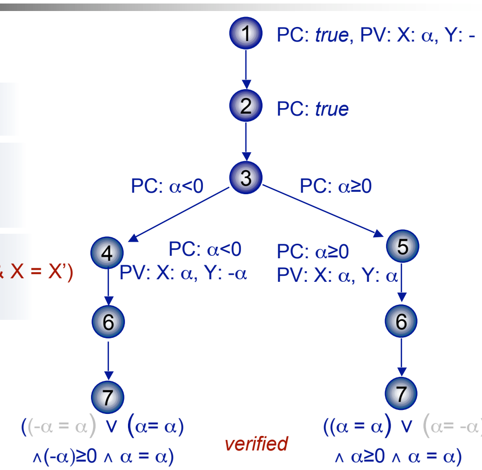
Symbolic Evaluation/Execution

- Creates a functional representation of a path of an executable component
- P is composed of partial functions corresponding to the executable paths
  $P = \{P_1, \ldots, P_r\}$
  $P_i : X_i \rightarrow Y$
- For a path P_i
  - $D[P_i]$ is the domain for path P_i
  - $C[P_i]$ is the computation for path P_i



Execution tree (Hantler-King)

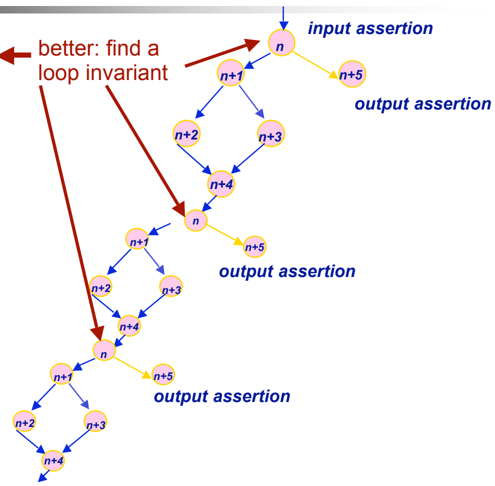
```
ABSOLUTE
assume (true)
procedure(X);
declare X,Y integer
if X<0
    then Y← -X;
    else Y← X;
return (Y);
prove((Y = X'|Y = -X') & Y≥0 & X = X')
end;
```



Loops -- unroll them?

```
        input assertion
n         do_while predicate1
n+1          if predicate2
n+2             then code ;
n+3             else code ;
n+4          end;
n+5       output assertion ;
```

better: find a loop invariant

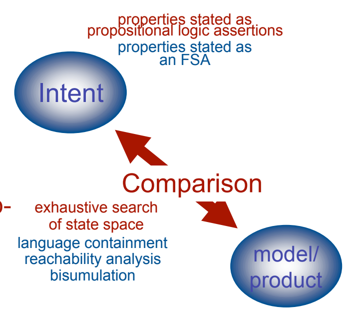


Straightforward Observations

- Problems
  - formal proofs are long, tedious and are often hard; assertions are hard to get right; invariants are difficult to get right (need to be invariant, but also need to support overall proof strategy)
- Unsuccessful proof attempt ⇒ ???
  - incorrect software? assertions? placement of assertion? inept prover? although failed proofs often indicate which of the above is likely to be true (especially to an astute prover)
- Deeper Issues
  - undecidability of predicate calculus ⇒ no way to be sure when you have a false theorem
  - there is no sure way to know when you should quit trying to prove a theorem (and change something)
  - proofs are generally much longer than the software being verified ⇒ errors in the proof are more likely than errors in the software being verified

Model Checking: Overview

- properties usually expressed in
  - in a propositional logic (e.g., temporal logic)
  - as a FSA
- system represented as a (possibly "abstracted") reachability graph
- reasoning engine
  - logic ⇒ propagates valid sub-formulas through the graph
  - FSA ⇒ compares FSAs via language inclusion; reachability; or bisumulation



Conservative Analysis

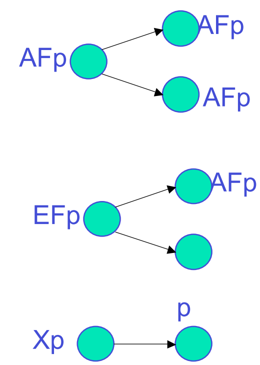
- If property is verified, property holds for all possible executions of the system
- If property is not verified:
  - an error found
    OR
  - a spurious result
- System model abstracts information to be tractable
  - Conservative abstractions usually over-approximate behavior
  - If inconsistency relies upon over-approximations, then a spurious result
  - e.g. all counter example correspond to infeasible paths

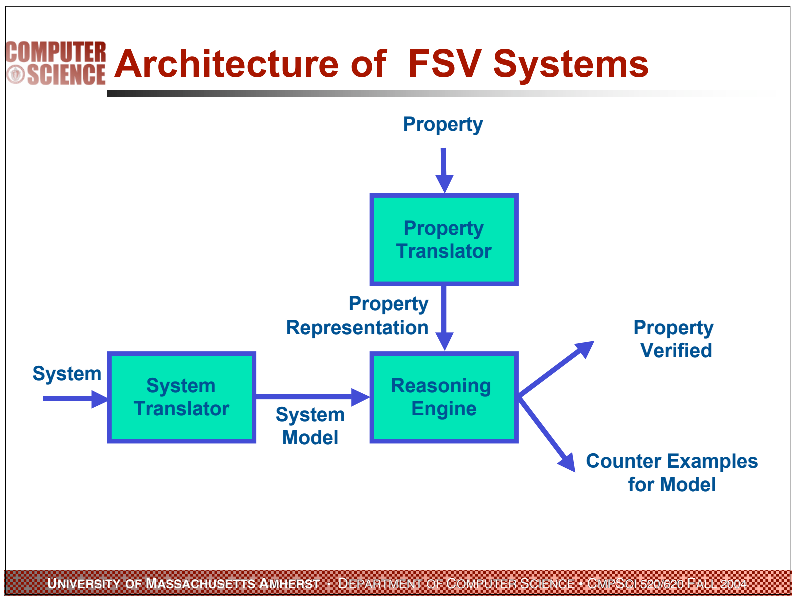
Temporal logic

- augments the standard operators of propositional logic with “tense” operators
- "possible worlds semantics" ⇒ Kripke model
  - relativize the truth of a statement to temporal stages or states
  - a statement is not simply true, but true at a particular state
  - states are temporally ordered, with the type of temporal order determined by the choice of axioms.
- model of time
  - partially ordered time
  - linearly ordered time
    - linear temporal logic is typically extended by two additional operators, “until” and “since”
  - discrete time
  - branching (nondeterministic) time
    - foundation for one of the principal approaches to verifying concurrent systems = Computational Tree Logics.

Computation Tree Logics

- specification language
  - a propositional temporal logic.
- verification procedure
  - exhaustive search of the state space of the concurrent system to determine truth of specification.
- formulas constructed from path quantifiers and temporal operators:
  - path quantifier:
    - A “for every path”
    - E “there exists a path”
  - temporal operator:
    - Xp “p holds next time’
    - Fp “p holds sometime in the future”
    - Gp “p holds globally in the future”
    - pUq “p holds until q holds”




COMPUTER SCIENCE
Architecture of FSV Systems
Property
Property Translator
Property Representation
System
System Translator
System Model
Reasoning Engine
Property Verified
Counter Examples for Model
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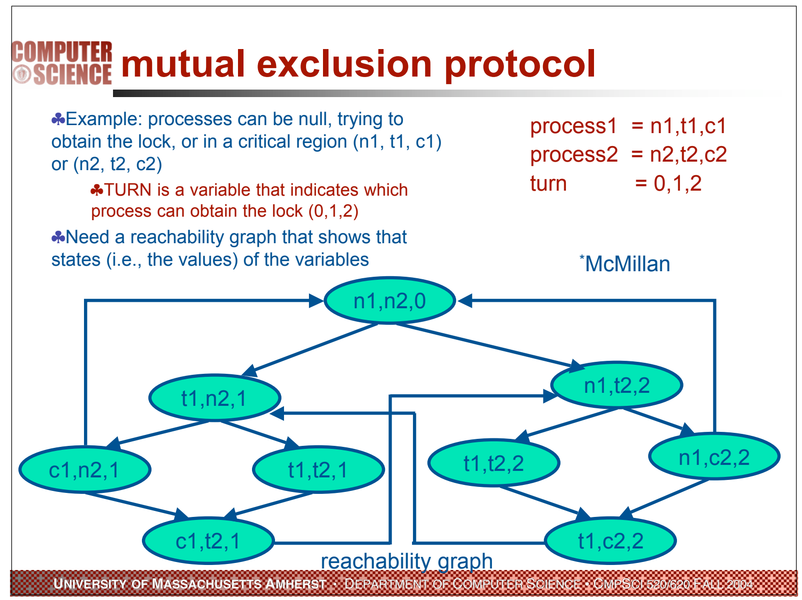
COMPUTER SCIENCE
mutual exclusion protocol
♣Example: processes can be null, trying to obtain the lock, or in a critical region (n1, t1, c1) or (n2, t2, c2)
♣TURN is a variable that indicates which process can obtain the lock (0,1,2)
♣Need a reachability graph that shows that states (i.e., the values) of the variables
process1 = n1,t1,c1
process2 = n2,t2,c2
turn = 0,1,2
*McMillan
n1,n2,0
t1,n2,1
n1,t2,2
c1,n2,1
t1,t2,1
t1,t2,2
n1,c2,2
c1,t2,1
t1,c2,2
reachability graph
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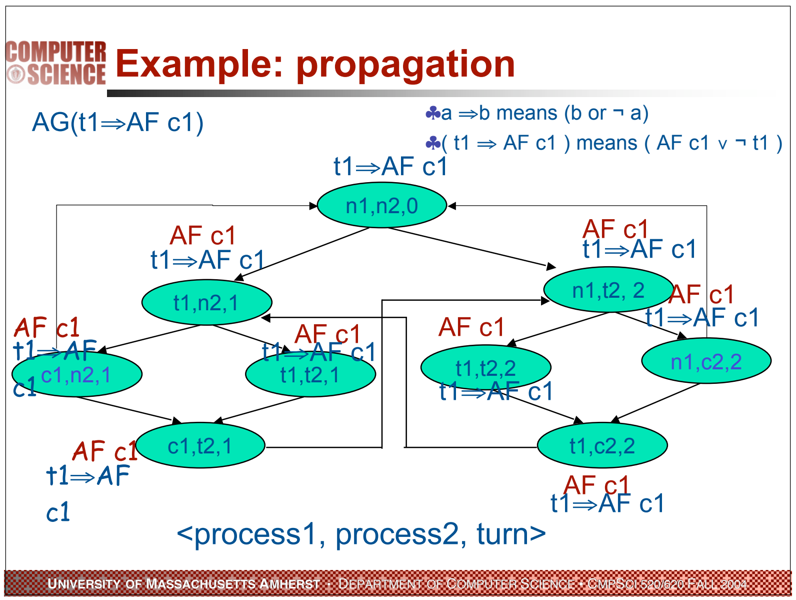
COMPUTER SCIENCE
Example: propagation
AG(t1⇒AF c1)
♣a ⇒b means (b or ¬ a)
♣(t1 ⇒ AF c1) means (AF c1 ∨ ¬ t1)
t1⇒AF c1
n1,n2,0
AF c1
t1⇒AF c1
t1,n2,1
n1,t2, 2
c1,n2,1
t1,t2,1
t1,t2,2
n1,c2,2
c1,t2,1
t1,c2,2
<process1, process2, turn>
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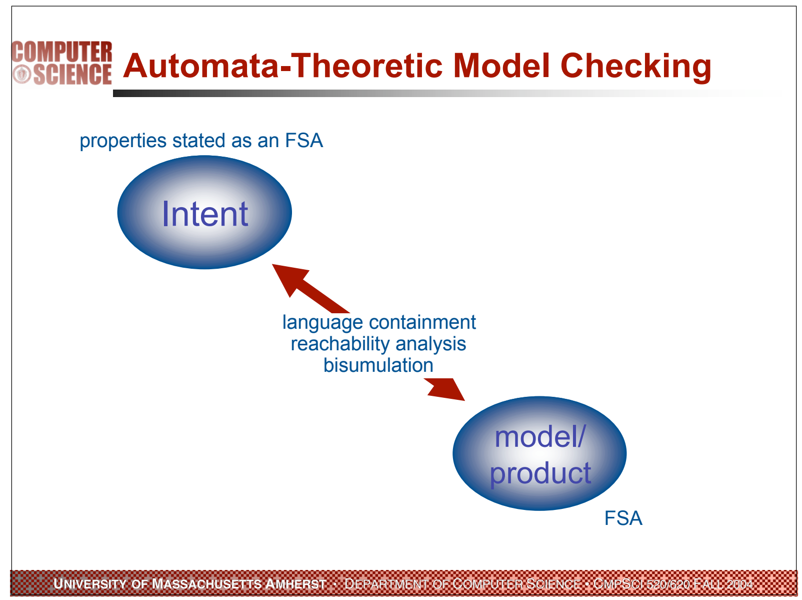
COMPUTER SCIENCE
Automata-Theoretic Model Checking
properties stated as an FSA
Intent
language containment
reachability analysis
bisumulation
model/
product
FSA
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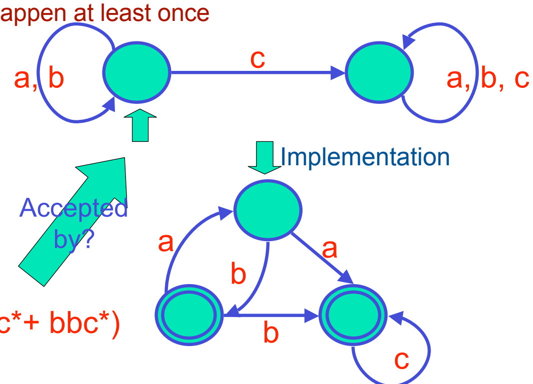
Example

- Specification:
  - of the possible observable events (a, b, c), c must happen at least once



(ba)*(ac*+ bbc*)

Some observations

- Model Checking
  - worst case bound linear in size of the model
    - but the model is exponential
  - not clear if model checking or symbolic model checking is superior
    - depends on the problem
  - experimentally often very effective!
    - used selectively to verify hardware designs
    - trying to develop appropriate abstractions to make it applicable to software systems

Verification

- How are they different?
  - (Automated) mathematical reasoning
    - difficult, error prone
    - decidability vs. expressiveness
      - Propositional calculus is decidable
      - Predicate calculus is semi-decidable
  - Finite-state verification
    - Reason about a finite model of the system
    - Fast, yields counterexamples, manages partial specifications, applies to concurrency
    - State explosion!

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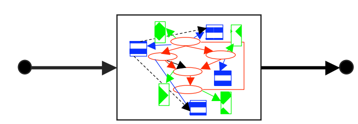
Types of Testing--what is tested

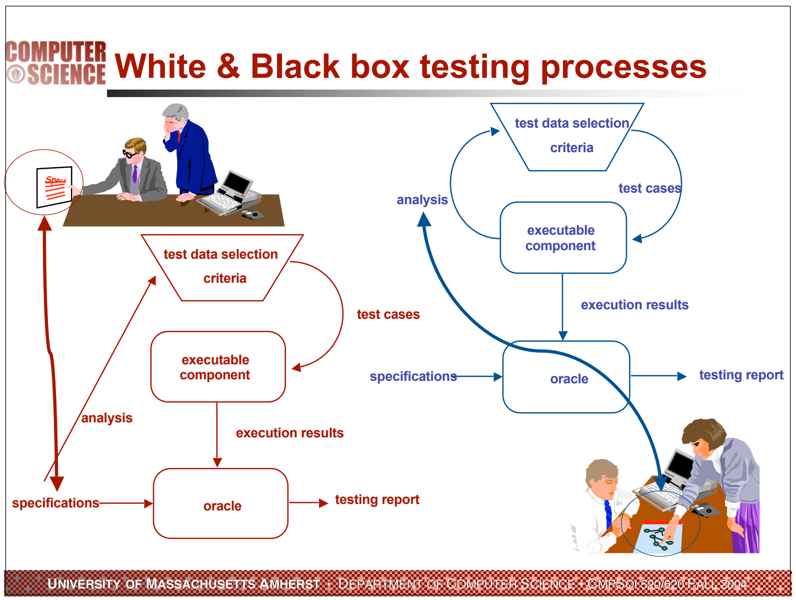
- Unit testing
  - exercise a single simple (procedure) component
- Integration testing
  - exercise a collection of inter-dependent components
  - focus on interfaces between components
- System testing
  - exercise a complete, stand-alone system
- Acceptance testing
  - customer's evaluation of a system
  - usually a form of system testing
- Regression testing
  - exercise a changed system
  - Focus on modifications or their impact

Testing approaches

- "black box"

- "white box" or "glass box"




COMPUTER SCIENCE
White & Black box testing processes
test data selection criteria
test cases
executable component
execution results
analysis
specifications
oracle
testing report
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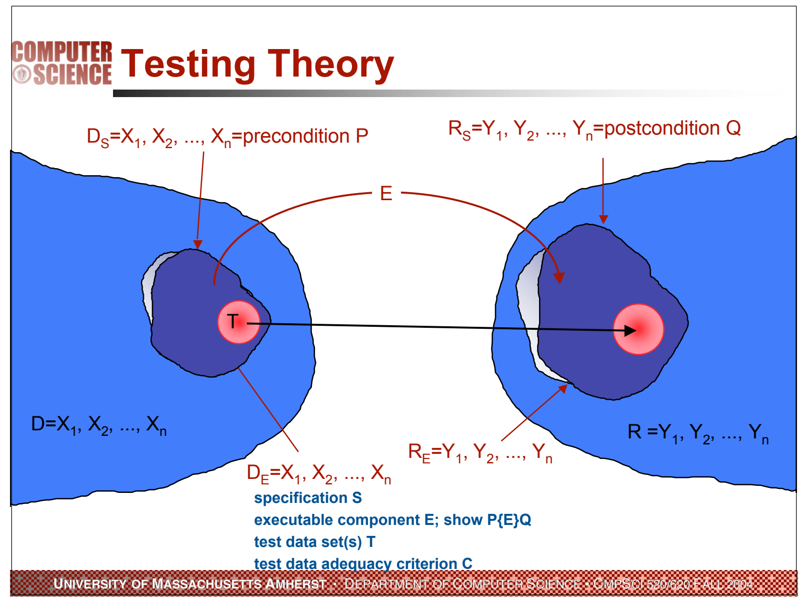
COMPUTER SCIENCE
Testing Theory
$D_S=X_1, X_2, ..., X_n$=precondition P
$R_S=Y_1, Y_2, ..., Y_n$=postcondition Q
E
T
$D=X_1, X_2, ..., X_n$
$R=Y_1, Y_2, ..., Y_n$
$D_E=X_1, X_2, ..., X_n$
$R_E=Y_1, Y_2, ..., Y_n$
specification S
executable component E; show P{E}Q
test data set(s) T
test data adequacy criterion C
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Testing Theory

- Criterion C for Test Adequacy
  - C:SxE ->2^T
  - specification-based — C (s) — "black box"
  - interface-based — C (x1, x2, ..., xn, y1, y2, ..., yn)
  - program-based — C (e)
  - combined — C (s,e) — "white box"
- Types
  - structural
  - fault-based
  - error-based
- if specification S defines a function F, such that P{F}Q, then C is *reliable* if $T_1, T_2, \ldots, T_m$; $C(T_i, E)$; and $D(E) \supseteq T_i$
  - $\forall T_i (\forall t \in T_i, E(t) = F(t)) \vee \forall T_i (\exists t \in T_i\ E(t) \neq F(t))$
  - $\forall t \in T_i, E(t) = F(t) \Rightarrow \forall t \in T_i\ OK(T_i) \Rightarrow E \equiv F$

Ideal Test Criterion

- test criterion C is *ideal* if for any executable component E and every test set $T_i \subseteq D(E)$ such that $C(T_i, E)$, T_i is successful
  - of course we want $T_i \ll D(E)$
  - but in general, T= D(P) is the only ideal test criterion
- In general, there is no ideal test criterion
  "Testing shows the presence, not the absence of bugs"
  E. Dijkstra
- Dijkstra was arguing that verification was better than testing
- but, verification has similar problems
  - can't prove an arbitrary program is correct
    - can't solve the halting problem
  - can't determine if the specification is complete
- need to use these techniques so that they compliment one another

Black Box Testing

- Functional/Interface Test Data Selection
  - typical cases
  - boundary conditions/values
  - illegal conditions (if robust)
  - fault-revealing cases
    - based on intuition about what is likely to break the system
  - other special cases
- stress testing
  - large amounts of data
  - worse case operating conditions
- combinations of events
  - select those cases that appear to be more error-prone
- common representations for selecting sequences of events
  - decision tables
  - cause and effect graphs
  - usage scenarios

"White Box" Test Data Selection

- structural
  - coverage based
- fault-based
  - e.g., mutation testing, RELAY
- error-based
  - domain and computation based
  - use representations created by symbolic execution

CFG-Based Coverage

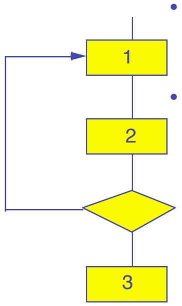
- Criteria
  - Statement Coverage
  - Path Coverage
  - Cyclomatic-number
  - Branch Coverage
  - Hidden Paths
  - Loop Guidelines
  - Boundary - Interior
- Selecting paths that satisfy the criteria
  - static selection
    - some of the associated paths may be infeasible
  - dynamic selection
    - monitors coverage and displays areas that have not been satisfactorily covered

"Simple" coverage measures

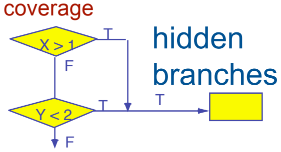
- Statement Coverage
  - requires that each statement in a program be executed at least once
    - a set P of paths in the CFP satisfies the statement coverage criterion iff $\forall\, n_i \in N, \ \exists\, p \in P$ such that n_i is on path p
- Path Coverage
  - Requires that every path in the program be executed at least once
    - P satisfies the path coverage criterion iff P contains all execution paths from the start node to the end node in the CFG
  - In most programs, path coverage is impossible
- Multiple Condition Coverage
  - T is adequate if for every condition C which consists of atomic predicates $(p_1, p_2, \ldots, p_n)$ and all possible combinations $(b_1, b_2, \ldots, b_n)$ of their values, there is at least one $t \in T$ such that the value of p_i is equal to b_i for all i

Branch & Loop Coverage

- Branch Coverage
  - Requires that each branch in a program (each edge in a control flow graph) be executed at least once
    - e.g., Each predicate must evaluate to each of its possible outcomes
  - Branch coverage is stronger than statement coverage



- Loop Coverage
  - Path 1, 2, 1, 2, 3 executes all branches (and all statements) but does not execute the loop well.
- Better
  - fall through case
  - minimum number of iterations
  - minimum +1 number of iterations
  - maximum number of iterations
  - maximum -1 number of iterations



hidden branches

1, 2, 1, 2, 1, 2, 3

$(1, 2)^{n-1}$, 3

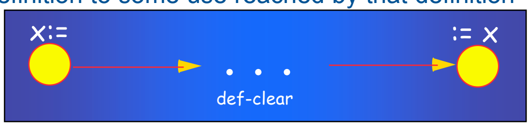
$(1, 2)^n$, 3

Data Flow Path Selection

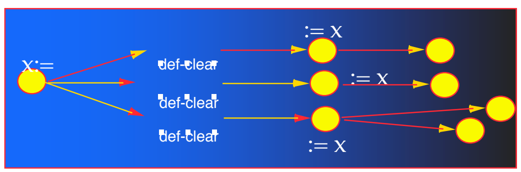
- Definitions
  - $d_n(x)$ denotes that variable x is assigned a value at node n (defined)
  - $u_m(y)$ denotes that variable y is used (referenced at node m)
    - a definition clear path p with respect to (wrt) x is a subpath where x is not defined at any of the nodes in p
    - a definition $d_m(x)$ reaches a use $u_n(x)$ iff there is a subpath (m) • p • (n) such that p is definition clear wrt x
- Rapps and Weyuker
  - definition-clear subpaths from definitions to uses
- Ntafos
  - chains of alternating definitions and uses linked by definition-clear subpaths
- Laski and Korel
  - combinations of definitions that reach uses at a node via a subpath

Rapps’ and Weyuker’s DF Criteria

- All-Defs - Some definition-clear subpath from each definition to some use reached by that definition



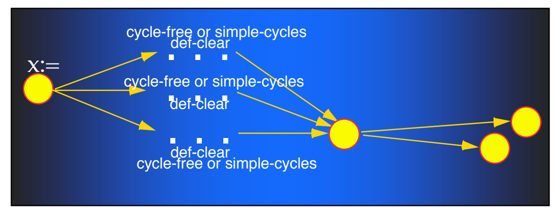
- All-Uses- Some definition-clear subpath from each definition to each use reached by that definition and each successor node of the use



Rapps’ and Weyuker’s DF Criteria

C-use is a “computation use”
P-use is a “predicate use”

- All-C-Uses, Some-P-Uses
  - either All-C-Uses for dm(x) or at least one P-Use
- All-P-Uses, Some-C-Uses
  - either All-P-Uses for dm(x) or at least one C-Use
- All-Du-Paths
  - All definition-clear subpaths that are cycle-free or simple-cycles from each definition to each use reached by that definition and each successor node of the use



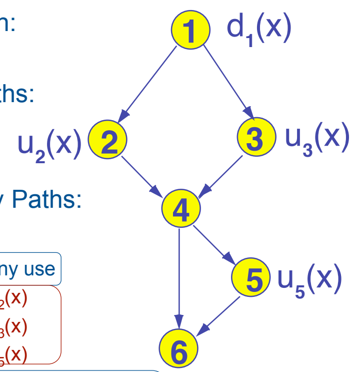
Examples

- All-Defs Satisfactory Path:
  - 1, 2, 4, 6
- All-Uses Satisfactory Paths:
  - 1, 2, 4, 5, 6
  - 1, 3, 4, 6
- All-Du-Paths Satisfactory Paths:
  - 1, 2, 4, 5, 6
  - 1, 3, 4, 5, 6

$d_1(x)$ to any use

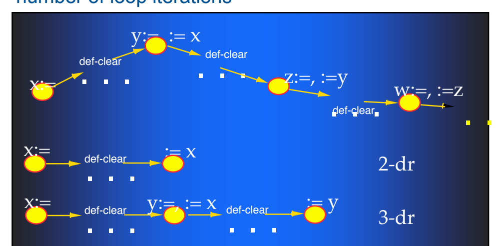
$d_1(x)$ to $u_2(x)$
$d_1(x)$ to $u_3(x)$
$d_1(x)$ to $u_5(x)$

$d_1(x)$ to $u_2(x)$
$d_1(x)$ to $u_3(x)$
both paths for $d_1(x)$ to $u_5(x)$



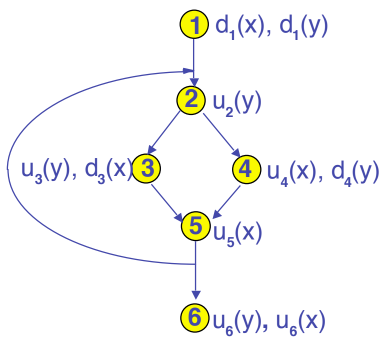
Ntafos k-dr Data Flow Criteria

- Chains of alternating definitions and uses linked by definition-clear subpaths (k-dr interactions)
  - ith definition reaches ith use,
  - which defines (i+1)st definition
- Required K-tuples
  - Some subpath propagating each k-dr interaction
    - + if last use is a predicate, both branches
    - + if first definition or last use is in a loop, minimal and some larger number of loop iterations



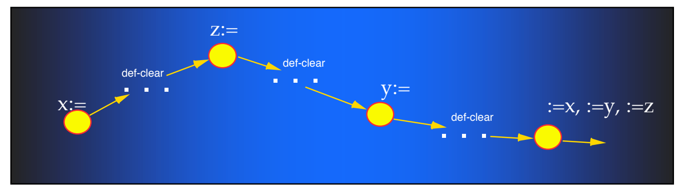
3-DR interactions

- d1(x), u4(x), d4(y), u6(y)
- d1(x), u4(x), d4(y), u2(y)
- d1(x), u4(x), d4(y), u3(y)
- d1(y), u3(y), d3(x), u5(x)
- d1(y), u3(y), d3(x), u6(x)
- d1(y), u3(y), d3(x), u4(x)
- d3(x), u4(x), d4(y), u6(y)
- d4(y), u3(y), d3(x), u5(x)
- d4(y), u3(y), d3(x), u6(x)
- Paths
  - 2-DR paths

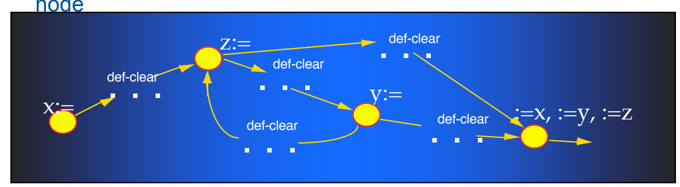


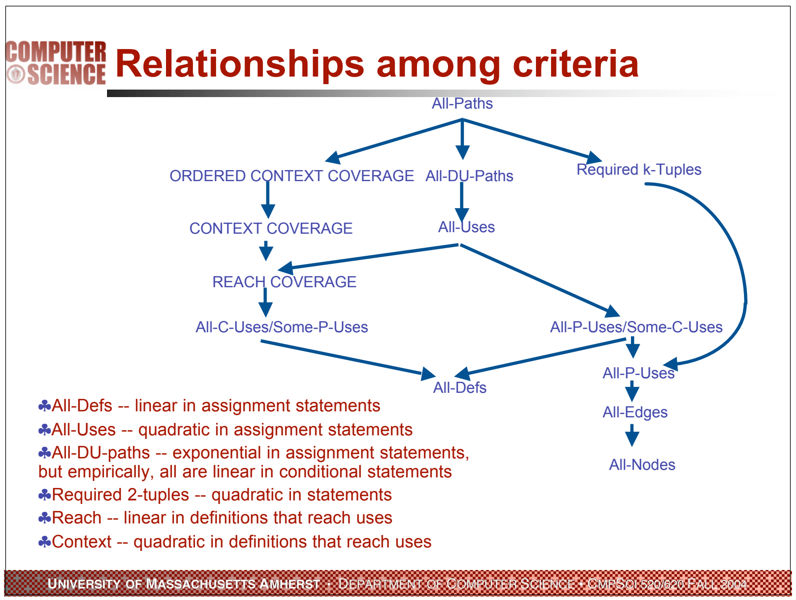
Laski's and Korel's Criteria

- Context Coverage - Some subpath along which each set of definitions reach uses at some node



- Ordered Context Coverage -Some subpath along which each ordering of each sequence of definitions reach uses at some node




COMPUTER SCIENCE
Relationships among criteria
All-Paths
ORDERED CONTEXT COVERAGE
All-DU-Paths
Required k-Tuples
CONTEXT COVERAGE
All-Uses
REACH COVERAGE
All-C-Uses/Some-P-Uses
All-P-Uses/Some-C-Uses
All-P-Uses
All-Defs
All-Edges
All-Nodes
♣All-Defs -- linear in assignment statements
♣All-Uses -- quadratic in assignment statements
♣All-DU-paths -- exponential in assignment statements, but empirically, all are linear in conditional statements
♣Required 2-tuples -- quadratic in statements
♣Reach -- linear in definitions that reach uses
♣Context -- quadratic in definitions that reach uses
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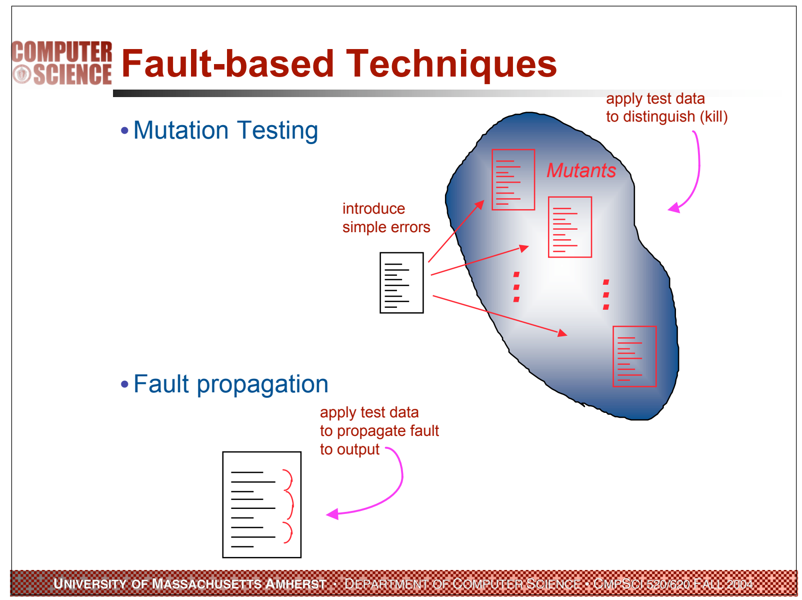
COMPUTER SCIENCE
Fault-based Techniques
• Mutation Testing
apply test data
to distinguish (kill)
Mutants
introduce
simple errors
• Fault propagation
apply test data
to propagate fault
to output
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COMPUTER SCIENCE Mutation Testing

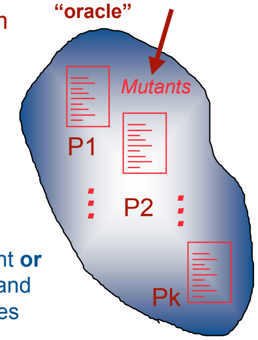
- Competent Programmer Hypothesis
  - programmers write programs that are reasonably close to the desired program
    - e.g., sort program is not written as a hash table
- Coupling Effect
  - detecting simple atomic faults will lead to the detection of more complex faults
- considers all simple (atomic) faults that could occur
  - introduces single faults one at a time to create "mutants" of original program
  - interactively(?) apply test data to complete (or partial) set of mutants
  - "test adequacy" is measured by "mutants killed"

operand mutations:
A : = X + 1; ⇒ A : = X + 2 or ⇒ A : = X + Y
binary operator replacement:
A : = X + 1; ⇒ A : = X - 1 or ⇒ A : = X * 1
statement replacement:
A : = X + 1; ⇒ continue or ⇒ return

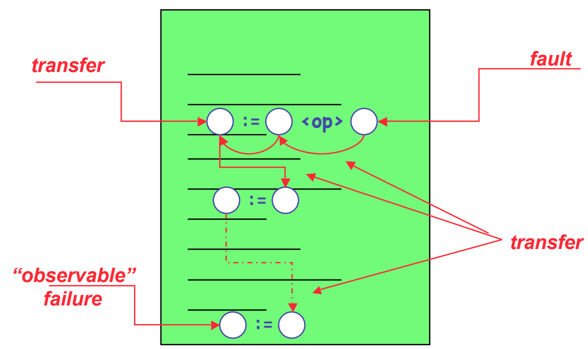
COMPUTER SCIENCE Mutation testing process

- Execute program P on test set T
  - save results R to serve as an oracle
  - P is considered the "correct" program
- Each fault results in a new program
  - Mutant programs = P1,...,Pk
- Execute each mutant Pi on T and compare results Ri to R
  - If Ri ≠ R then mutant is killed
  - if Ri = R then either
    - Pi = P, thus it is an **equivalent** mutant **or** the test cases do not reveal the error and **need to find a new test case** that does

apply test data to distinguish (kill) by comparing output with "oracle"



Relay Model



Other Fault-Based techniques:

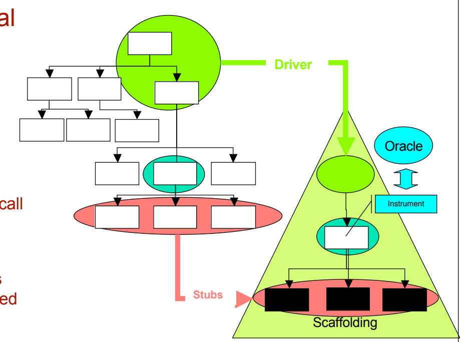
- mutating test data
  - instead of mutating program, mutate input
- Bart Miller did an experiment where he demonstrated that arbitrary strings caused UNIX to consistently fail
  - wanted to understand why storms caused his connection to go down

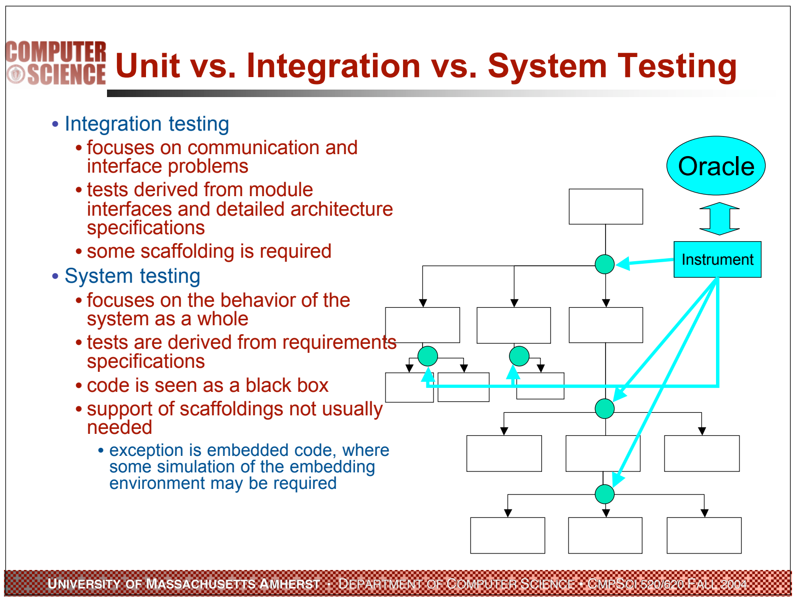
Putting it all together

- unit testing
- integration & system testing
- regression testing

Unit testing

- test scaffolding
  - can be created for general or for specific tests
  - is composed of
    - one or more drivers
      - provide a prototype activation environment
      - drivers initialize non-local variables and parameters and call the unit
    - one or more stubs
      - provide a prototype of the units used by the program to be tested
    - one or more oracles
      - identify the tests that cause failures.





COMPUTER SCIENCE
Unit vs. Integration vs. System Testing
• Integration testing
• focuses on communication and interface problems
• tests derived from module interfaces and detailed architecture specifications
• some scaffolding is required
• System testing
• focuses on the behavior of the system as a whole
• tests are derived from requirements specifications
• code is seen as a black box
• support of scaffoldings not usually needed
• exception is embedded code, where some simulation of the embedding environment may be required
Oracle
Instrument
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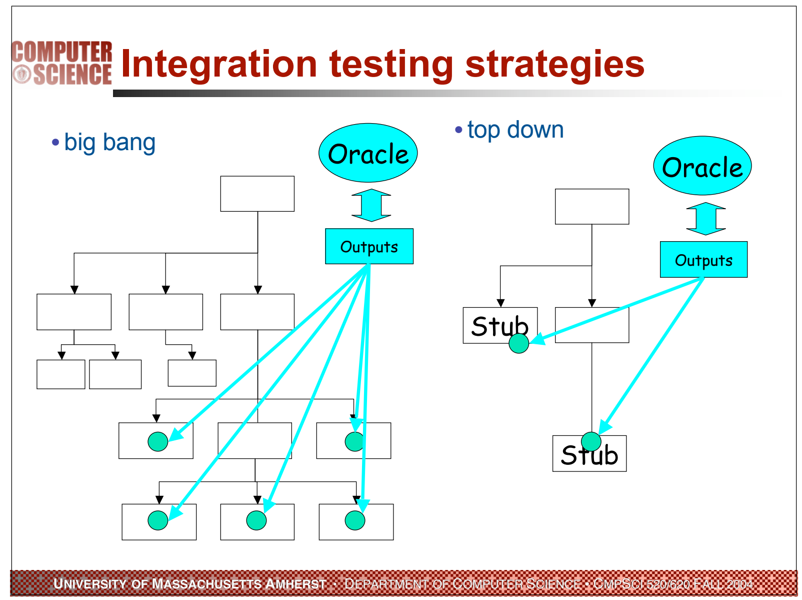

COMPUTER SCIENCE
Integration testing strategies
• big bang
Oracle
Outputs
• top down
Oracle
Outputs
Stub
Stub
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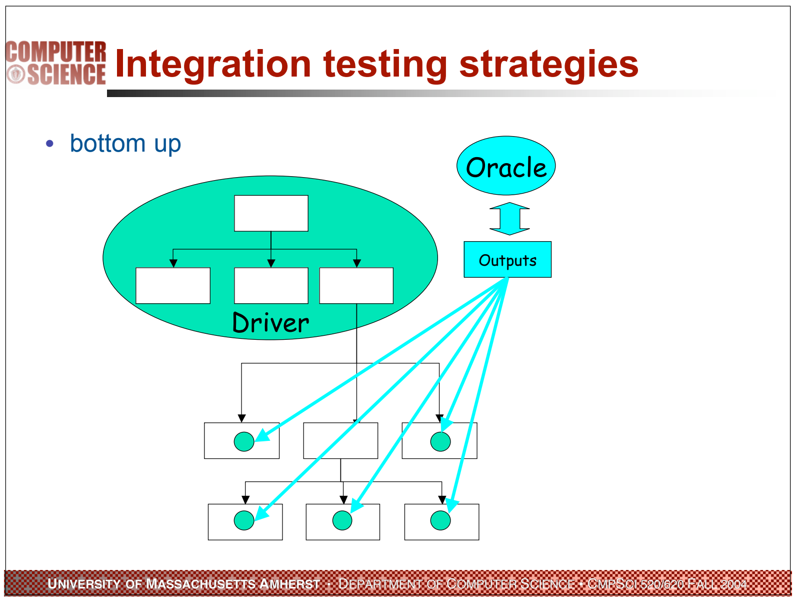
COMPUTER SCIENCE
Integration testing strategies
• bottom up
Oracle
Outputs
Driver
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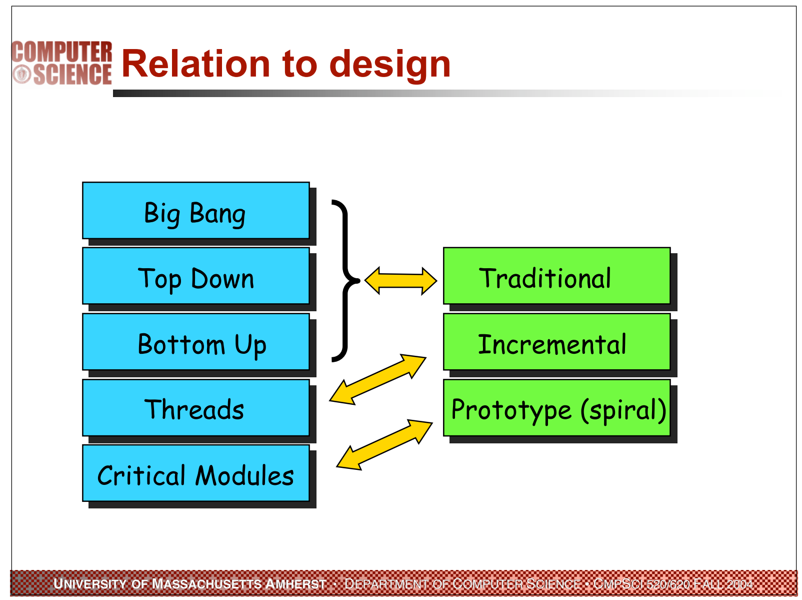
COMPUTER SCIENCE
Relation to design
Big Bang
Top Down
Bottom Up
Threads
Critical Modules
Traditional
Incremental
Prototype (spiral)
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O-O Programs are Different

- High Degree of Reuse
  - Does this mean more, or less testing?
- Unit Testing vs. Class Testing
  - What is the right "unit" in OO testing?
- Review of Analysis & Design
  - Classes appear early, so defects can be recognized early as well

Testing OOA and OOD Models

- Correctness (of each model element)
  - Syntactic (notation, conventions)
    - review by modeling experts
  - Semantic (conforms to real problem)
    - review by domain experts
- Consistency (of each class)
  - Revisit Class Diagram
  - Trace delegated responsibilities
  - Examine / adjust cohesion of responsibilities
- Evaluating the Design
  - Compare behavioral model to class model
  - Compare behavioral & class models to the use cases
  - Inspect the detailed design for each class (algorithms & data structures)

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Unit Testing

- What is a "Unit"?
  - Traditional: a "single operation"
  - O-O: encapsulated data & operations
- Smallest testable unit = class
  many operations
- Inheritance
  - testing "in isolation" is impossible
  - operations must be tested every place they are used

Issues in O-O testing

- Need to re-examine all testing techniques and processes
  - Primary Issues:
    - implications of encapsulation
    - implications of inheritance
    - implications of genericity
    - implications of polymorphism
  - Changes concerns
    - State of instance variables
    - Sequences of methods calls
    - Must test a class and its specializations

Example

```
Base::describedSelf() is this code
        if (val < 0) message("Less")
        else if(val==0) message("Equal")
        else message("More")
```

Tests:

input	expected output
-1	Less
0	Equal
1	More

Tests:

	input	expected output
OK	-1	Less
Change	0	~~Equal~~ Zero Equal
OK	1	More
Add	42	Jackpot

```
Derived::describedSelf() is this code
        if (val < 0) message("Less")
        else if(val==0) message("Zero Equal")
        else
        {
            message("More")
            if(val==42) message("Jackpot")
        }
```


White-box vs. Black-box Testing

- The distance between object-oriented specification and implementation is typically small
  - gap (and therefore usefulness) of the white-box/black-box distinction is decreasing
- But object-oriented specification describes functional behavior, while the implementation describes how that is achieved
- These techniques can be adapted to method testing, but are not sufficient for class testing
- Conventional flow-graph approaches
  - may be inconsistent the object-oriented paradigm
  - method-level control faults are not likely

Black-box O-O Testing

- Conventional black-box methods are useful for object-oriented systems
  - error-guessing strategies
  - verification of ADTs can be adapted to object-oriented systems
- Other approaches
  - utilize specifications integrated with the implementation as assertions
    - specification integrated with the implementation as dynamic assertions
    - C++ assertions or Eiffel pre/post-conditions offer similar self-checking
  - Utilize method (event) sequence information
    - usually don't have history of method invocations so can't do this with assertions

Encapsulation

- not a source of errors but may be an obstacle to testing
- how to get at the concrete state of an object?
- use the abstraction
  - state is inspected via access methods
  - equivalence scenarios
    - comparing sequences of events
    - state is implicitly inspected by comparing related behavior
  - examine sequences of events
    - need to be able to define what are equivalent sequences and need to determine equal states
- use or provide hidden functions to examine the state
  - useful for debugging throughout the life of the system
    - but modified code, may alter the behavior
    - especially true for languages that do not support strong typing
- proof-of-correctness techniques
  - a proved method could be excused from testing to bootstrap testing of other methods
  - state reporting methods tend to be small and simple, they should be relatively easy to prove

Implications of Inheritance

- rule rather than the exception?
- inherited features usually require re-testing
  - because a new context of usage results when features are inherited
  - multiple inheritance increases the number of contexts to test
- specialization relationships
  - implementation specialization should correspond to problem domain specialization
  - reusability of superclass test cases depends on this

Which fns must be tested

Base class contains:
inherited(int x)
redefined() - returns a number in range 1 to 10 inclusive

Derived class contains:
redefined() - returns a number in range 0 to20 inclusive
//inherited() is inherited

- derived::redefined has to be tested afresh
- does derived::inherited() have to be retested?

```
inherited contains the code:
        if (x<0)
           x = x/redefined()
        return x
```

have to test when x<0, could divide by 0

- derived::inherited() may not have to be completely tested
  - if code in inherited() doesn't depend on redefined(), doesn't call it nor call any code that indirectly calls it

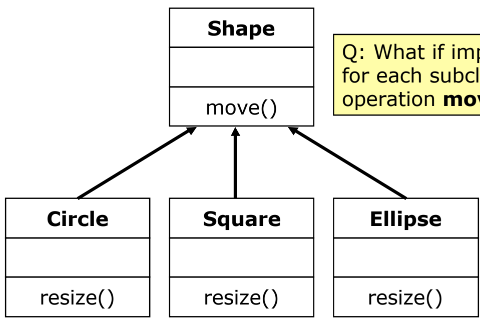
Inheritance Testing

- flattening inheritance
  - each subclass is tested as if all inherited features were newly defined
  - tests used in the super-classes can be reused
  - many tests are redundant
- incremental testing
  - reduce tests only to new/modified features
  - determining what needs to be tested requires automated support

Polymorphism

- in procedural programming, procedure calls are statically bound
- each possible binding of a polymorphic component requires a separate set of test cases
  - many server classes may need to be integrated before a client class can be tested
- may be hard to determine all such bindings
- complicates integration planning and testing

Testing under Inheritance



Q: What if implementation of **resize()** for each subclass calls inherited operation **move()** ?

A: Shape cannot be completely tested unless we also test Circle, Square, & Ellipse!

Integration Testing

- O-O Integration: Not Hierarchical
  - Coupling is not via subroutine
  - “Top-down” and “Bottom-up” have little meaning
- Integrating one operation at a time is difficult
  - Indirect interactions among operations

O-O Integration Testing

- Thread-Based Testing
  - Integrate set of classes required to respond to one input or event
  - Integrate one thread at a time
  - Example: Event-Dispatching Thread vs. Event Handlers in Java
    - Implement & test all GUI events first
    - Add event handlers one at a time
- Use-Based Testing
  - Implement & test independent classes first
  - Then implement dependent classes (layer by layer, or cluster-based)
  - Simple driver classes or methods sometimes required to test lower layers

Test Case Design

- Focus: "Designing sequences of operations to exercise the states of a class instance"
- Challenges
  - Observability - Do we have methods that allow us to inspect the inner state of an object?
  - Inheritance - Can test cases for a superclass be used to test a subclass?
- Test Case Checklist
  - Identify unique tests & associate with a particular class
  - Describe purpose of the test
  - Develop list of testing steps:
    - Specified states to be tested
    - Operations (methods) to be tested
    - Exceptions that might occur
    - External conditions & changes thereto
    - Supplemental information (if needed)

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