Verification

Outline

- What are the goals of verification?
- What are the main approaches to verification?
  - What kind of assurance do we get through testing?
  - How can testing be done systematically?
  - How can we remove defects (debugging)?
- What are the main approaches to software analysis?
  - informal vs. formal

Need for verification

- Designers are fallible even if they are skilled and follow sound principles
- Everything must be verified, every required quality, process and products
  - even verification itself…

Properties of verification

- May not be binary (OK, not OK)
  - severity of defect is important
  - some defects may be tolerated
- May be subjective or objective
  - e.g., usability
- Even implicit qualities should be verified
  - because requirements are often incomplete
  - e.g., robustness

Approaches to verification

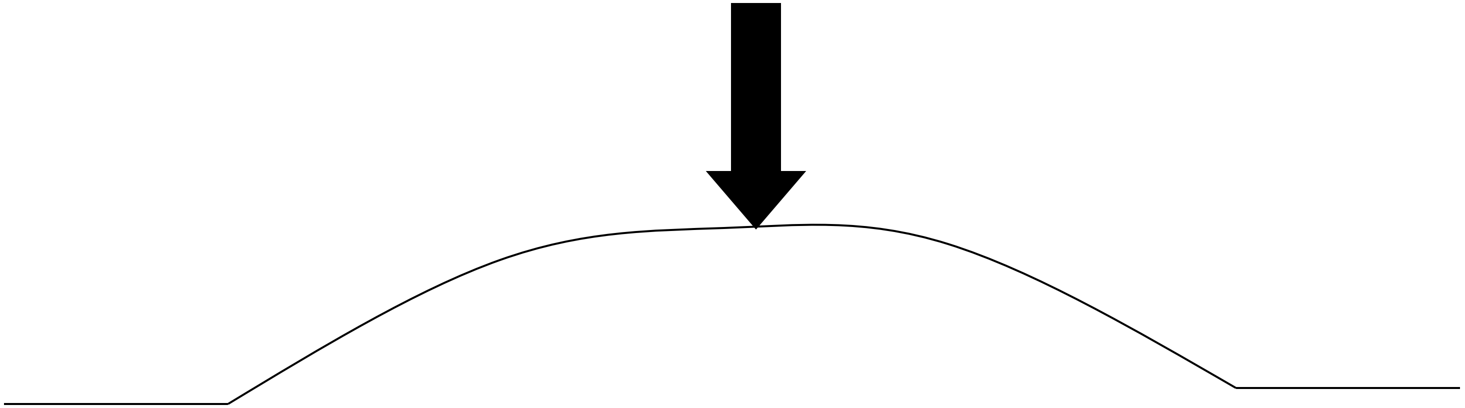
- Experiment with behavior of product
  - sample behaviors via testing
  - goal is to find "counterexamples"
  - dynamic technique
- Analyze product to deduce its adequacy
  - analytic study of properties
  - static technique

Testing and lack of "continuity"

- Testing samples behaviors by examining "test cases"
- Impossible to extrapolate behavior of software from a finite set of test cases
- No continuity of behavior
  - it can exhibit correct behavior in infinitely many cases, but may still be incorrect in some cases

Verification in engineering

- Example of bridge design
- One test assures infinite correct situations



```
procedure binary-search (key: in element;
                         table: in elementTable; found: out Boolean) is
begin
    bottom := table'first; top := table'last;
    while bottom < top loop
        if (bottom + top) rem 2 ≠ 0 then
            middle := (bottom + top - 1) / 2;
        else
            middle := (bottom + top) / 2;
        end if;
        if key ≤ table (middle) then
            top := middle;
        else
            bottom := middle + 1;
        end if;
    end loop;
    found := key = table (top);
end binary-search
```

if we omit this the routine works if the else is never hit! (i.e. if size of table is a power of 2)

Goals of testing

- To show the *presence* of bugs (Dijkstra, 1987)
- If tests do detect failures, we cannot conclude that software is defect-free
- Still, we need to do testing
  - driven by sound and systematic principles

Goals of testing (cont.)

- Should help isolate errors
  - to facilitate debugging
- Should be repeatable
  - repeating the same experiment, we should get the same results
    - this may not be true because of the effect of execution environment on testing
    - because of nondeterminism
- Should be accurate

Theoretical foundations of testing

Definitions (1)

- P (program), D (input domain), R (output domain)
  - P: D $\rightarrow$ R (may be partial)
- Correctness defined by OR $\subseteq$ D $\times$ R
  - P(d) correct if $<d, P(d)> \in$ OR
  - P correct if all P(d) are correct

Definitions (2)

- FAILURE
  - P(d) is not correct
    - may be undefined (error state) or may be the wrong result
- ERROR (DEFECT)
  - anything that may cause a failure
    - typing mistake
    - programmer forgot to test “x = 0”
- FAULT
  - incorrect intermediate state entered by program

Definitions (3)

- Test case t
  - an element of D
- Test set T
  - a finite subset of D
- Test is successful if P(t) is correct
- Test set successful if P correct for all t in T

Definitions (4)

- Ideal test set T
  - if P is incorrect, there is an element of T such that P(d) is incorrect
- *if an ideal test set exists for any program, we could prove program correctness by testing*

Test criterion

- A criterion C defines finite subsets of D (test sets)
  - $C \subseteq 2^D$
- A test set T satisfies C if it is an element of C

Example

$C = \{<x_1, x_2, \ldots, x_n> \mid n \geq 3 \wedge \exists\, i, j, k, (x_i<0 \wedge x_j=0 \wedge x_k>0)\}$

<-5, 0, 22> is a test set that satisfies C

<-10, 2, 8, 33, 0, -19> also does

<1, 3, 99> does not

Properties of criteria (1)

- C is consistent
  - for any pairs T1, T2 satisfying C, T1 is successful iff T2 is successful
    - so either of them provides the “same” information
- C is complete
  - if P is incorrect, there is a test set T of C that is not successful
- C is complete and consistent
  - identifies an ideal test set
  - allows correctness to be proved!

Properties of criteria (2)

- C1 is finer than C2
  - for any program P
    - for any T1 satisfying C1 there is a subset T2 of T1 which satisfies C2

Properties of definitions

- None is effective, i.e., no algorithms exist to state if a program, test set, or criterion has that property
- In particular, there is no algorithm to derive a test set that would prove program correctness
  - there is no constructive criterion that is consistent and complete

Empirical testing principles

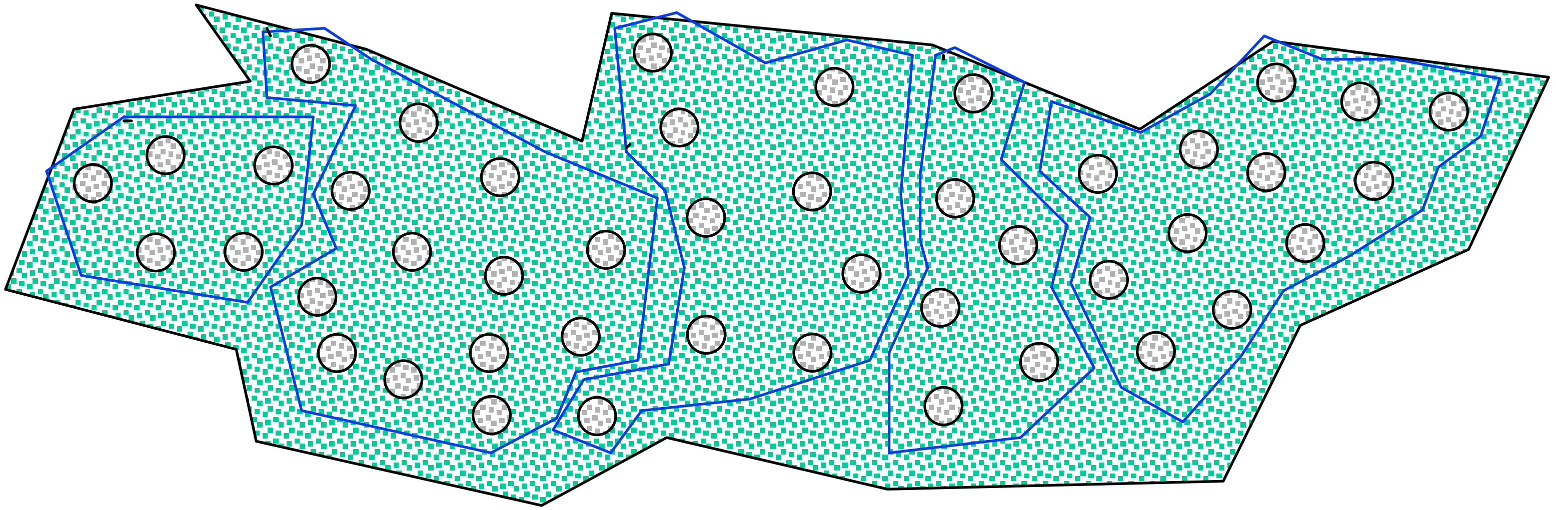
- Attempted compromise between the impossible and the inadequate
- Find strategy to select significant test cases
  - significant=has high potential of uncovering presence of error

Complete-Coverage Principle

- Try to group elements of D into subdomains D1, D2, …, Dn where any element of each Di is likely to have similar behavior
  - $D = D1 \cup D2 \cup \ldots \cup Dn$
- Select one test as a representative of the subdomain
- If $Dj \cap Dk \neq \emptyset$ for all j, k (partition), any element can be chosen from each subdomain
- Otherwise choose representatives to minimize number of tests, yet fulfilling the principle

Complete-Coverage Principle

example of a partition



Testing in the small

We test individual modules

- BLACK BOX (functional) testing
  - partitioning criteria based on the module’s specification
  - tests *what the program is supposed to do*
- WHITE BOX (structural) testing
  - partitioning criteria based on module’s internal code
  - tests *what the program does*

White box testing

derives test cases from program code

Structural Coverage Testing

- (In)adequacy criteria
  - If significant parts of program structure are not tested, testing is inadequate
- Control flow coverage criteria
  - Statement coverage
  - Edge coverage
  - Condition coverage
  - Path coverage

Statement-coverage criterion

- Select a test set T such that every elementary statement in P is executed at least once by some d in T
  - an input datum executes many statements → try to minimize the number of test cases still preserving the desired coverage

Example

```
read (x); read (y);
if x > 0 then
        write ("1");
else
        write ("2");
end if;
if y > 0 then
        write ("3");
else
        write ("4");
end if;
```

{<x = 2, y = 3>, <x = - 13, y = 51>, <x = 97, y = 17>, <x = - 1, y = - 1>} covers all statements

{<x = - 13, y = 51>, <x = 2, y = - 3>} is minimal

Weakness of the criterion

```
if x < 0 then
        x := -x;
end if;
z := x;
```

{<x=-3} covers all statements

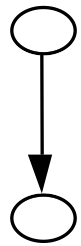
it does not exercise the case when x is positive and the then branch is not entered

Edge-coverage criterion

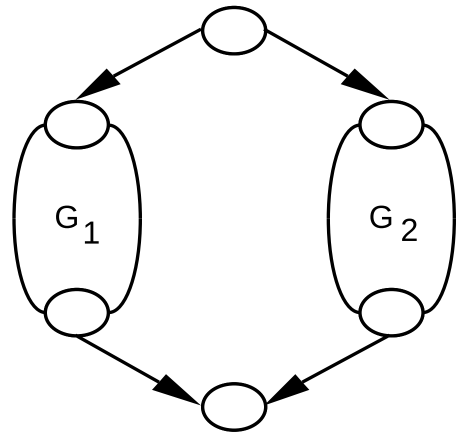
- Select a test set T such that every edge (branch) of the control flow is exercised at least once by some d in T

  this requires formalizing the concept of the control graph, and how to construct it
  - edges represent statements
  - nodes at the ends of an edge represent entry into the statement and exit

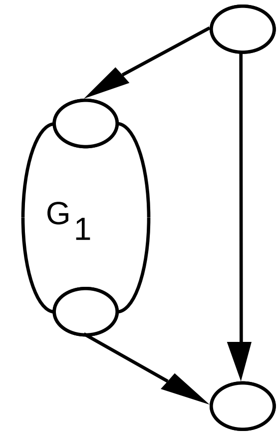
Control graph construction rules



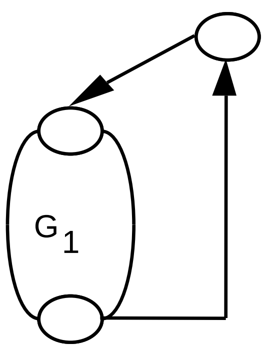
I/O, assignment, or procedure call



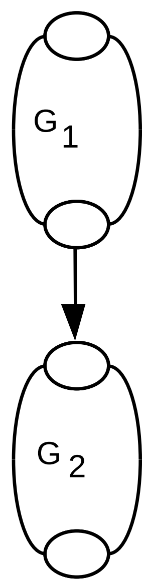
if-then-else



if-then



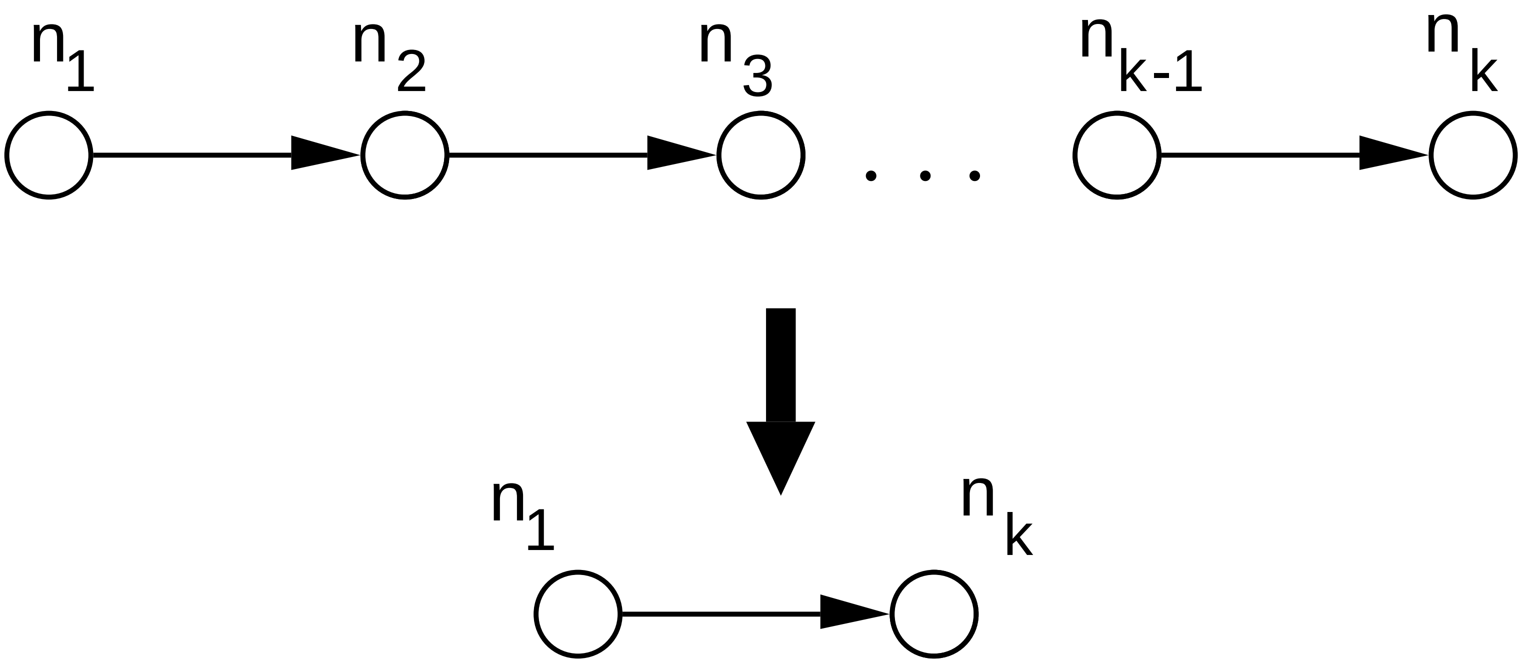
while loop



two sequential statements

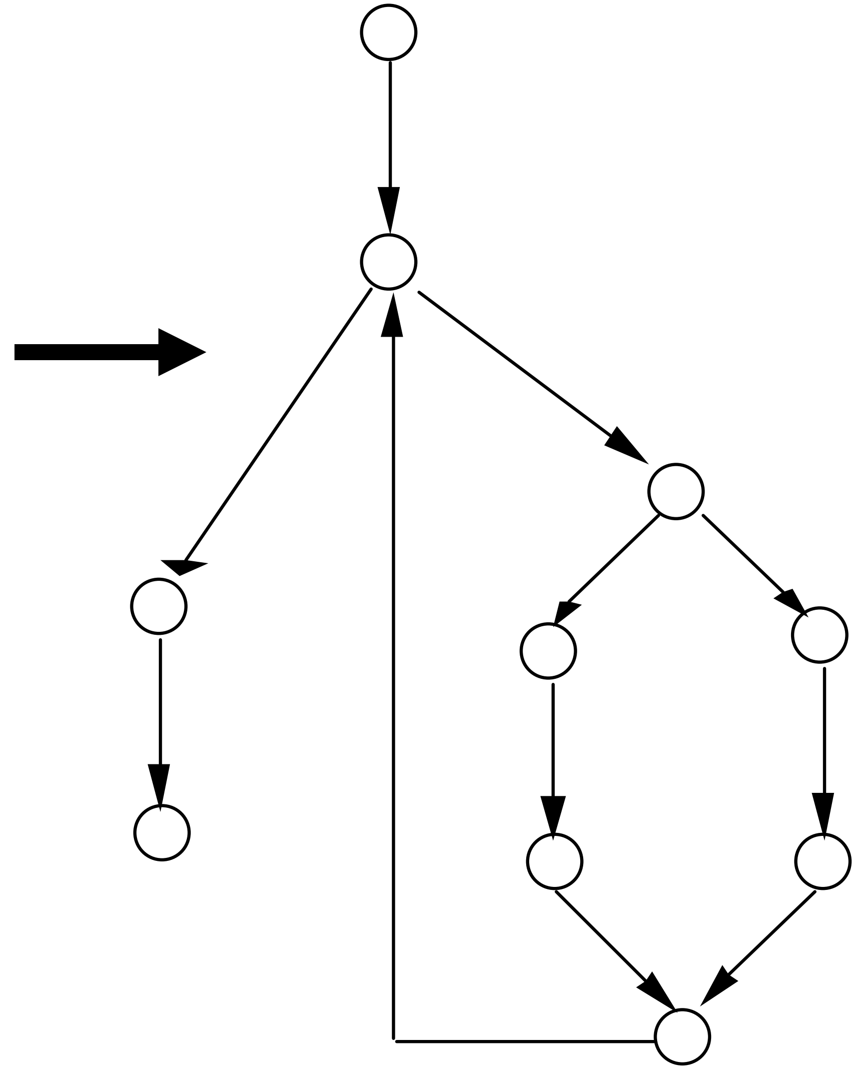
Simplification

a sequence of edges can be collapsed into just one edge



Exemple: Euclid's algorithm

```
begin
        read (x); read (y);
        while x ≠ y loop
                if x > y then
                        x := x - y;
                else
                        y := y - x;
                end if;
        end loop;
        gcd : = x;
end;
```



Weakness

```
found := false; counter := 1;
while (not found) and counter < number_of_items loop
        if table (counter) = desired_element then
                found := true;
        end if;
        counter := counter + 1;
end loop;
if found then
        write ("the desired element is in the table");
else
        write ("the desired element is not in the table");
end if;
```

test cases: (1) empty table, (2) table with 3 items, second of which is the item to look for

do not discover error (< instead of ≤)

Condition-coverage criterion

- Select a test set T such that every edge of P's control flow is traversed and all possible values of the constituents of compound conditions are exercised at least once
  - it is finer than edge coverage

Weakness

```
if x ≠ 0 then
        y := 5;
else
        z := z - x;
end if;
if z > 1 then
        z := z / x;
else
        z := 0;
end if;
```

{<x = 0, z = 1>, <x = 1, z = 3>} causes the execution of all edges, but fails to expose the risk of a division by zero

Path-coverage criterion

- Select a test set T which traverses all paths from the initial to the final node of P's control flow
  - it is finer than previous kinds of coverage
  - however, number of paths may be too large, or even infinite (see while loops)
    - additional constraints must be provided

The infeasibility problem

- Syntactically indicated behaviors (statements, edges, etc.) are often impossible
  - unreachable code, infeasible edges, paths, etc.
- Adequacy criteria may be impossible to satisfy
  - manual justification for omitting each impossible test case
  - adequacy “scores” based on coverage
    - example: 95% statement coverage

Further problem

- What if the code omits the implementation of some part of the specification?
- White box test cases derived from the code will ignore that part of the specification!

Black box testing

derives test cases from specifications

The specification

The program receives as input a record describing an invoice. (A detailed description of the format of the record is given.) The invoice must be inserted into a file of invoices that is sorted by date. The invoice must be inserted in the appropriate position: If other invoices exist in the file with the same date, then the invoice should be inserted after the last one. Also, some consistency checks must be performed: The program should verify whether the customer is already in a corresponding file of customers, whether the customer's data in the two files match, etc.

Did you consider these cases?

- An invoice whose date is the current date
- An invoice whose date is before the current date

(This might be even forbidden by law)
This case, in turn, can be split into the two following subcases:

- An invoice whose date is the same as that some existing invoice
- An invoice whose date does not exist in any previously recorded invoice
- Several incorrect invoices, checking different types of inconsistencies

Systematic black-box techniques

- Testing driven by logic specifications (pre and postconditions)
- Syntax-driven testing
- Decision table based testing
- Cause-effect graph based testing

Logic specification of insertion of invoice record in a file

for all x in Invoices, f in Invoice_Files
{sorted_by_date(f) and not exist j, k (j ≠ k and f(j) =f(k)}

insert(x, f)

{sorted_by_date(f) and
for all k (old_f(k) = z implies exists j (f(j) = z)) and
for all k (f(k) = z and z ≠ x) implies exists j (old_f(j) = z) and
exists j (f(j). date = x. date and f(j) ≠ x) implies j < pos(x, f) and
result ≡ x.customer belongs_to customer_file and
warning ≡ (x belongs_to old_f or x.date < current_date or ....)
}

Apply coverage criterion to postcondition...
Rewrite in a more convenient way...

TRUE implies
    sorted_by_date(f) and for all k old_f(k) = z
    implies exists j (f(j) = z) and
    for all k (f(k) = z and z ≠ x) implies exists j (old_f(j) = z)
and
(x.customer belongs_to customer_file) implies result
and
not (x.customer belongs_to customer_file and ...)
    implies not result
and
x belongs_to old_y implies warning
and
x.date < current_date implies warning
and
....

Syntax-driven testing (1)

- Consider testing an interpreter of the following language

<expression> ::= <expression> + <term>|
<expression> - <term> | <term>
<term> ::= <term> * <factor> | <term> /
<factor> | <factor>
<factor> ::= ident | (<expression>)

Syntax-driven testing (2)

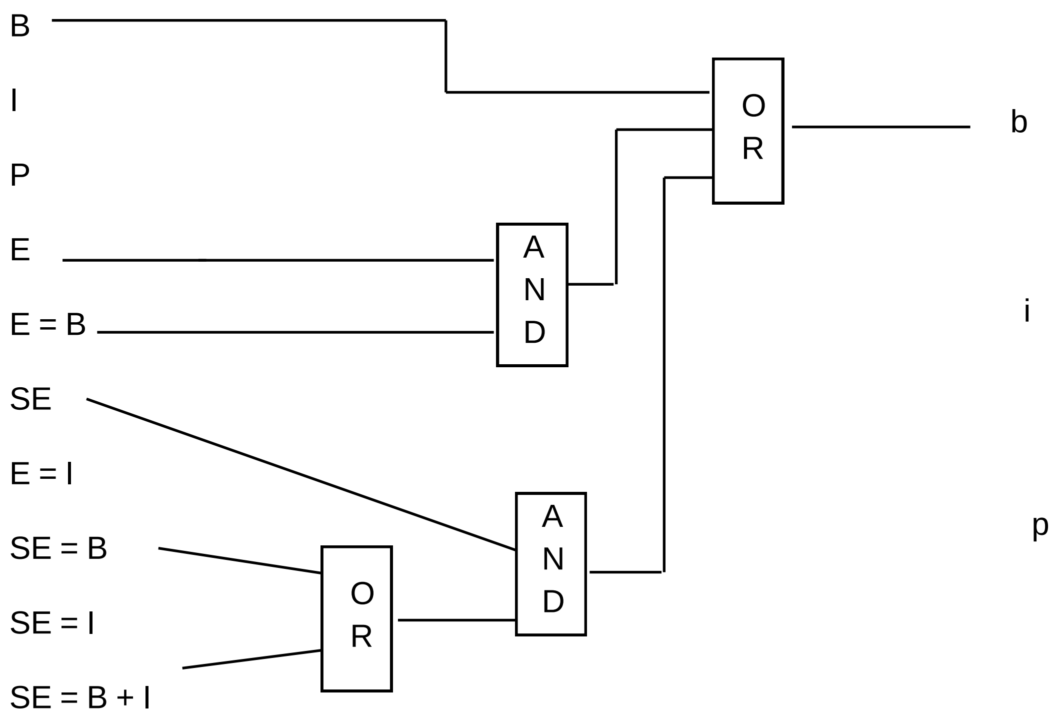
- Apply complete coverage principle to all grammar rules
- Generate a test case for each rule of the grammar
  - note, however that the test case might also cover other rules
- Note: the specification is formal, and test generation can be automated

Decision-table-based testing

"The word-processor may present portions of text in three different formats: plain text (p), boldface (b), italics (i). The following commands may be applied to each portion of text: make text plain (P), make boldface (B), make italics (I), emphasize (E), super emphasize (SE). Commands are available to dynamically set E to mean either B or I (we denote such commands as E=B and E=I, respectively.) Similarly, SE can be dynamically set to mean either B (command SE=B) or I (command SE=I), or B and I (command SE=B+I.)"

P	*								
B		*							*
I			*						*
E				*	*				
SE						*	*	*	
E = B				*					
E = I					*				
SE = B						*			
SE = I							*		
SE = B + I								*	
action	**p**	**b**	**i**	**b**	**i**	**b**	**i**	**b,i**	**b,i**

Cause effect graphs

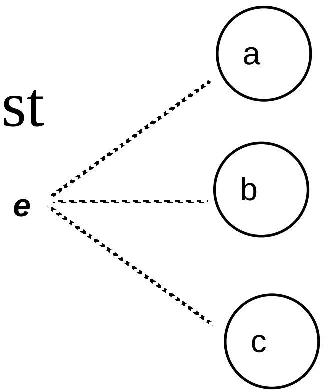


The AND/OR graph represents the correspondence between causes and effects

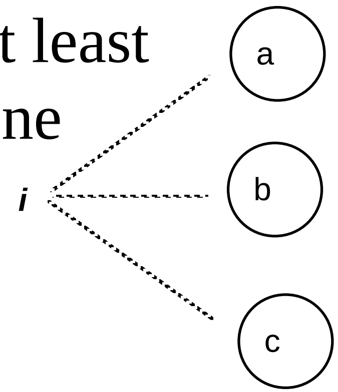
Further constraints

"Both B and I exclude P (i.e., one cannot ask both for plain text and, say, italics for the same portion of text.) E and SE are mutually exclusive."

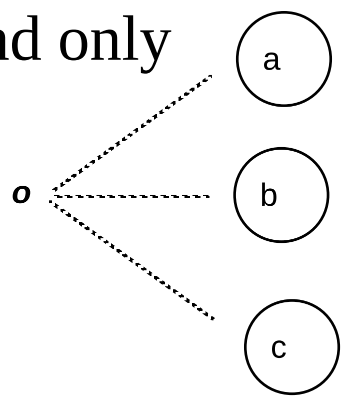
at most one



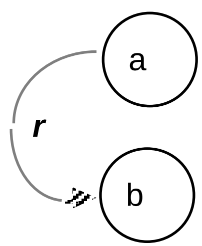
at least one



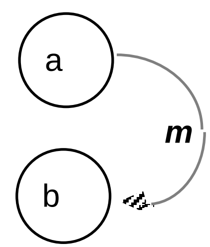
one and only one

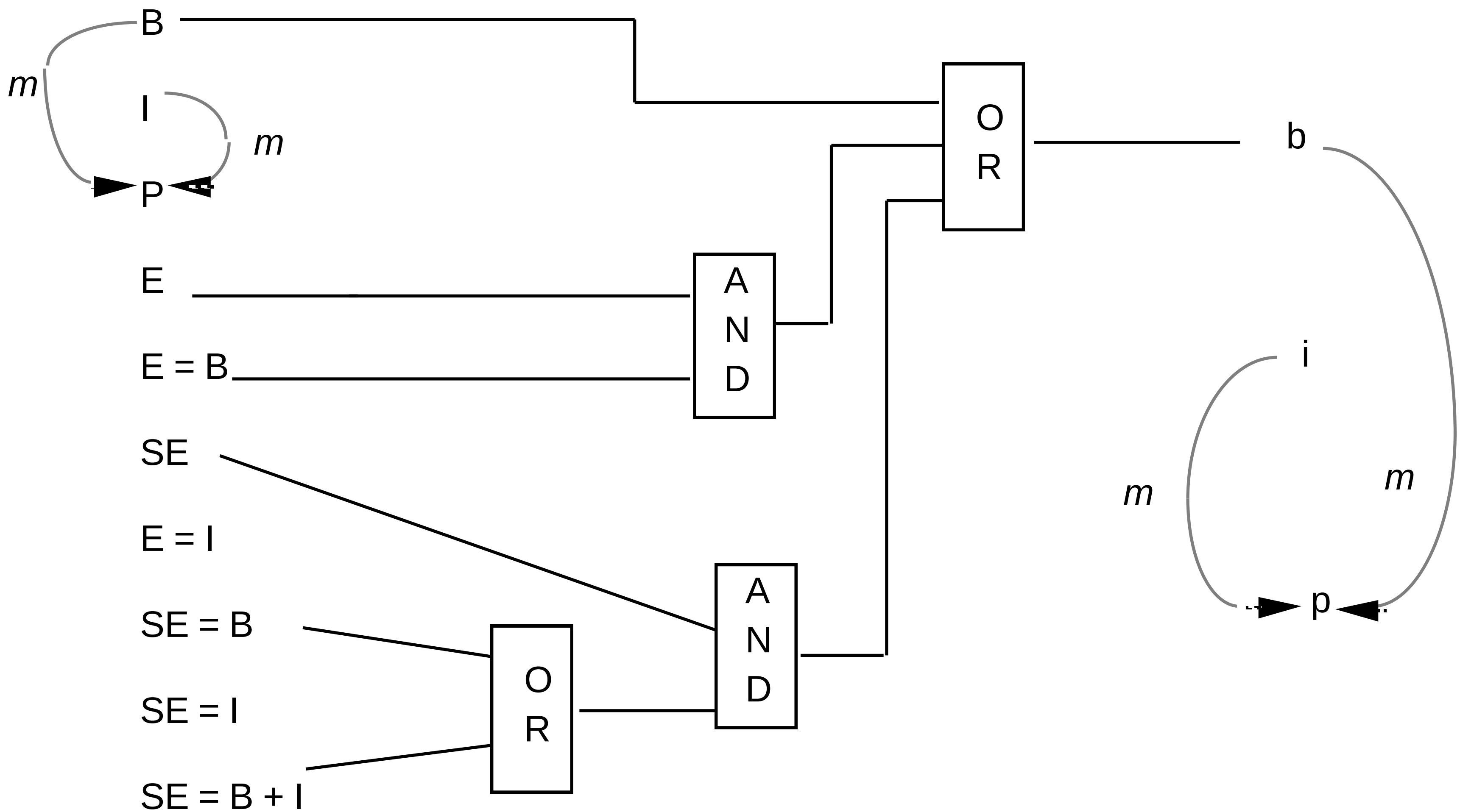


requires



masks





X m Y = X implies not Y

Coverage criterion

- Generate all possible input combinations and check outputs
- May reduce the number by going backwards from outputs
  - OR node with true output:
    - use input combinations with only one true input
  - AND node with false output:
    - use input combinations with only one false input

Testing boundary conditions

- Testing criteria partition input domain in classes, assuming that behavior is "similar" for all data within a class
- Some typical programming errors, however, just happen to be at the boundary between different classes

Criterion

- After partitioning the input domain D into several classes, test the program using input values not only “inside” the classes, but also at their boundaries
- This applies to both white-box and black-box techniques

The oracle problem

How to inspect the results of test executions to reveal failures

- Oracles are required at each stage of testing
- Automated test oracles are required for running large amounts of tests
- Oracles are difficult to design - no universal recipe

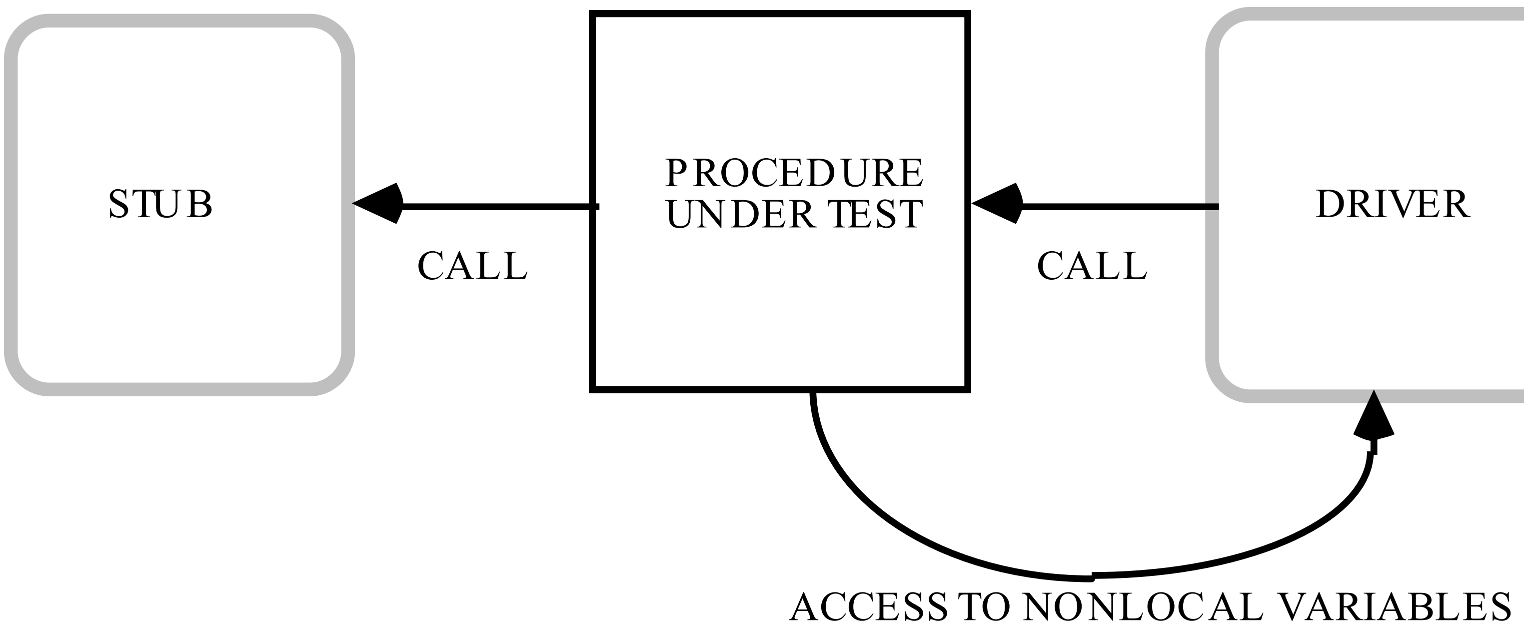
Testing in the large

- Module testing
  - testing a single module
- Integration testing
  - integration of modules and subsystems
- System testing
  - testing the entire system
- Acceptance testing
  - performed by the customer

Module testing

- Scaffolding needed to create the environment in which the module should be tested
  - stubs
    - modules used by the module under test
  - driver
    - module activating the module under test

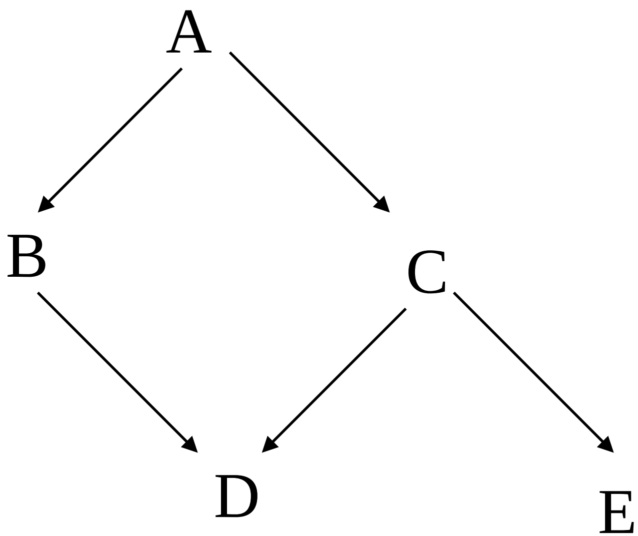
Testing a functional module



Integration testing

- Big-bang approach
  - first test individual modules in isolation
  - then test integrated system
- Incremental approach
  - modules are progressively integrated and tested
    - can proceed both top-down and bottom-up according to the USES relation

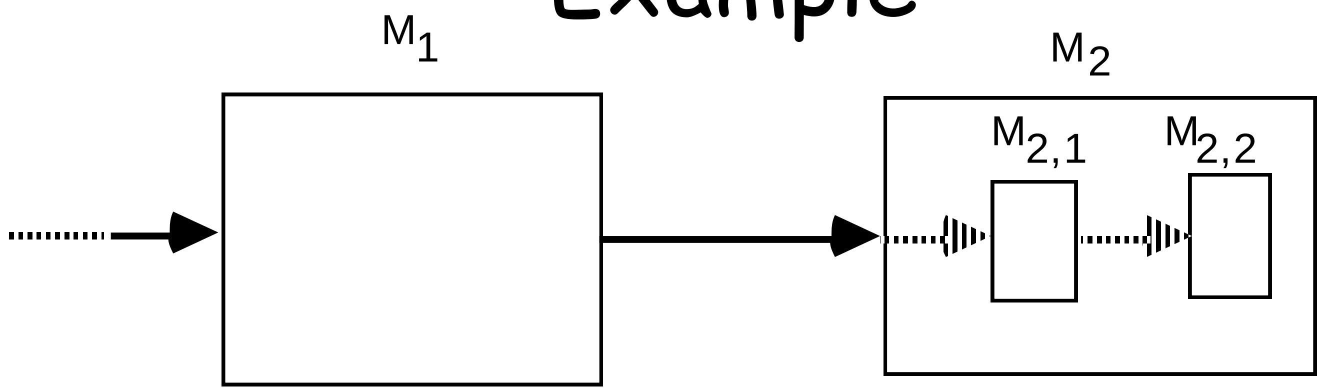
Integration testing and USES relation



If integration and test proceed bottom-up only need drivers

Otherwise, if we proceed top-down only stubs are needed

Example



M1 USES M2 and M2 IS_COMPOSED_OF {M2,1, M2,2}

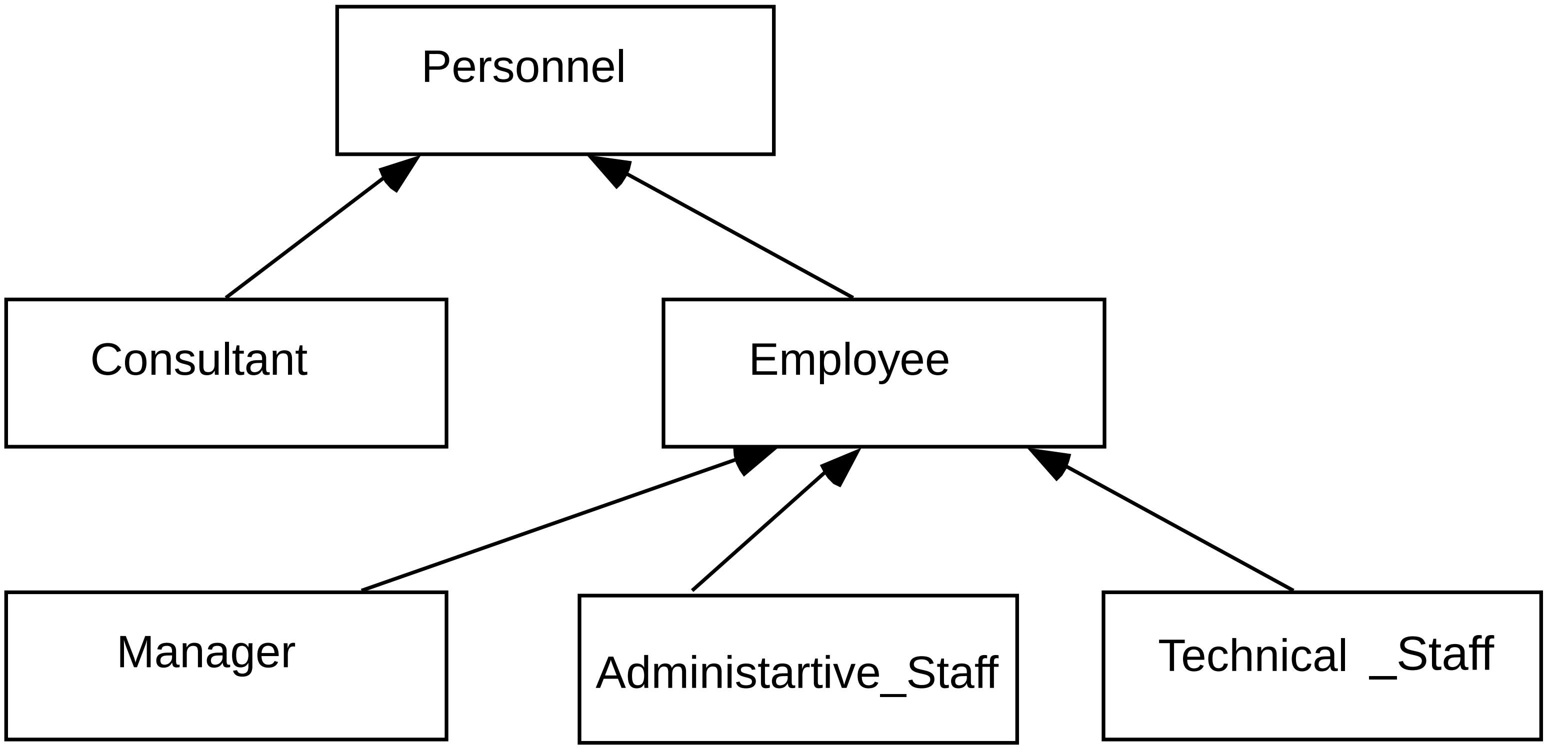
CASE 1
Test M1, providing a stub for M2 and a driver for M1
Then provide an implementation for M2,1 and a stub for M2,2

CASE 2
Implement M2,2 and test it by using a driver,
Implement M2,1 and test the combination of M2,1 and M2,2 (i.e., M2) by using a driver
Finally, implement M1 and test it with M2, using a driver for M1

Testing OO programs

- New issues
  - inheritance
  - genericity
  - polymorphism
  - dynamic binding
- Open problems still exist

Inheritance



How to test classes of the hierarchy?

- "Flattening" the whole hierarchy and considering every class as a totally independent component
  - does not exploit incrementality
- Finding an ad-hoc way to take advantage of the hierarchy

A sample strategy

- A test that does not have to be repeated for any heir
- A test that must be performed for heir class X and all of its further heirs
- A test that must be redone by applying the same input data, but verifying that the output is not (or *is*) changed
- A test that must be modified by adding other input parameters and verifying that the output changes accordingly

Separate concerns in testing

- Testing for functionality is not enough
- Overload testing
- Robustness testing
- Regression testing
  - organize testing with the purpose of verifying possible *regressions* of software during its life—that is, degradations of correctness or other qualities due to later modifications

Testing concurrent and real-time systems

- Nondeterminism inherent in concurrency affects repeatability
- For real-time systems, a test case consists not only of input data, but also of the times when such data are supplied

Analysis

Analysis vs. testing

- Testing characterizes a *single* execution
- Analysis characterizes a *class* of executions; it is based on a *model*
- They have complementary advantages and disadvantages

Informal analysis techniques Code walkthroughs

- Recommended prescriptions
  - Small number of people (three to five)
  - Participants receive written documentation from the designer a few days before the meeting
  - Predefined duration of meeting (a few hours)
  - Focus on the *discovery* of errors, not on fixing them
  - Participants: designer, moderator, and a secretary
  - Foster cooperation; no evaluation of people
    - Experience shows that most errors are discovered by the designer during the presentation, while trying to explain the design to other people.

Informal analysis techniques Code inspection

- A reading technique aiming at error discovery
- Based on checklists; e.g.:
  - use of uninitialized variables;
  - jumps into loops;
  - nonterminating loops;
  - array indexes out of bounds;
  - …

Correctness proofs

A program and its specification (Hoare notation)

```
{true}
begin
        read (a); read (b);
        x := a + b;
        write (x);
end
{output = input1 + input2}
```

proof by backwards substitution

Proof rules

Notation:

If Claim 1 and Claim 2 have been proven, one can deduce Claim3

$$\frac{\text{Claim1, Claim2}}{\text{Claim3}}$$

Proof rules for a language

$$\frac{\{F1\}S1\{F2\},\ \{F2\}S2\{F3\}}{\{F1\}S1;S2\{F3\}}$$

sequence

if-then-else

$$\frac{\{\text{Pre and cond}\}\ S1\ \{\text{Post}\},\{\text{Pre and not cond}\}\ S2\ \{\text{Post}\}}{\{\text{Pre}\}\ \text{if cond then S1 ; else S 2 ; end if;}\ \{\text{Post}\}}$$

while-do

$$\frac{\{\text{I and cond}\}\ S\ \{I\}}{\{I\}\ \text{while cond loop S; end loop;}\ \{\text{I and not cond}\}}$$

I *loop invariant*

Correctness proof

- Partial correctness
  - validity of {Pre} Program {Post} guarantees that if the Pre holds before the execution of Program, *and if the program ever terminate*s, then Post will be achieved
- Total correctness
  - Pre guarantees Program's termination *and* the truth of Post

These problems are undecidable!!!

Example

```
{input1 > 0 and input2 > 0}
begin
        read (x); read (y);
        div := 0;
        while x =y loop
                div := div + 1;
                x := x - y;
        end loop;
        write (div); write (x);
end;
{input1 = output1 * input2 + output2 and
0 =output2 < input2 }
```

Invention of loop invariant

- Difficult and creative step
- Cannot be constructed automatically
- In the example

  input1 = div * y + x and x =0 and y = input2

Programs with arrays

{Pre} a(i) := expression; {Post}

Pre denotes the assertion obtained from Post by substituting every occurrence of an indexed variable a(j) by the term

if j = i then expression else a(j);

Example

```
{n =1}
i := 1; j := 1;
found := false;
while i =n loop
        if table (i) = x then
                found := true;
                i := i + 1
        else
                table (j) := table (i);
                i := i + 1; j := j + 1;
        end if;
end loop;
n := j - 1;
{not exists m (1 =m =n and table (m) = x) and
found =exists m (1 =m =old_n and old_table (m) = x)}
```

*old*_table, *old*_n constants denoting the values of table and of n before execution of the program fragment

Correctness proof

- Can be done by using the following loop invariant

  {(j =i) and (i =*old*_n + 1) and

  (not exists m (1 =m < j and

  table (m) = x)) and (n = *old*_n) and

  found = exists m (1 =m < i and

  *old*_table(m) = x)}

Correctness proofs in the large

- We can prove correctness of operations (e.g., operations on an abstract data type)
- Then use the result of the proof in proving fragments that operate on objects of the ADT

Example

```
module TABLE;
exports
        type Table_Type (max_size: NATURAL): ?;
        no more than max_size entries may be
        stored in a table; user modules must guarantee this
        procedure Insert (Table: in out TableType ;
                ELEMENT: in ElementType);
        procedure Delete (Table: in out TableType;
                ELEMENT: in ElementType);
        function Size (Table: in Table_Type) return NATURAL;
        provides the current size of a table
        …
end TABLE
```

Having proved these

{true}
Delete (Table, Element);
{Element $\notin$ Table};

{Size (Table) < max_size}
Insert (Table, Element)
{Element $\in$ Table};

We can then prove properties of programs using tables
For example, that after executing the sequence

Insert(T, x);
Delete(T, x);

x is not present in T

An assessment of correctness proofs

- Still not used in practice
- However
  - may be used for very critical portions
  - assertions may be the basis for a systematic way of inserting runtime checks
  - proofs may become more practical as more powerful support tools are developed
  - knowledge of correctness theory helps programmers being rigorous

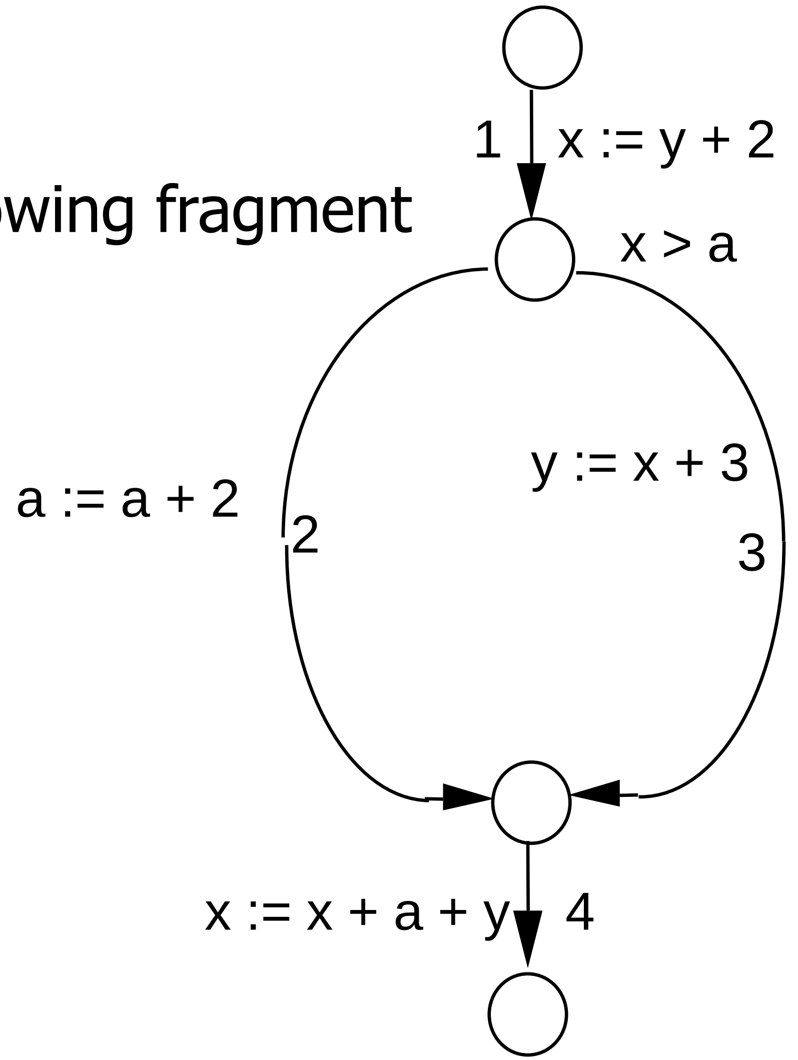
Symbolic execution

- Can be viewed as a middle way between testing and analysis
- Executes the program on symbolic values
- One symbolic execution corresponds to many actual executions

Example(1)

Consider executing the following fragment with x=X, y=Y, a=A

```
x := y + 2;
if x > a then
        a := a + 2;
else
        y := x + 3;
end if;
x := x + a + y;
```



Example(2)

- When control reaches the conditional, symbolic values do not allow execution to select a branch
- One can choose a branch, and record the choice in a *path condition*
- Result:

<{a = A, y = Y + 5, x = 2 * Y + A + 7},

$\underbrace{\text{<1, 3, 4>}}_{\text{execution path}}$, $\underbrace{Y + 2 \le A\text{>}}_{\text{path condition}}$

Symbolic execution rules (1)

symbolic state:
<symbolic_variable_values, execution_path, path_condition>

- read (x)
  - removes any existing binding for x and adds binding x = X, where X is a *newly introduced* symbolic value
- Write (expression)
  - output(n) = computed_symbolic_value (n counter initialized to 1 and automatically incremented after each output statement)

Symbolic execution rules (2)

- x:= expression
  - construct symbolic value of expression, SV; replace previous binding for x with x = SV
- After execution of the last statement of a sequence that corresponds to an edge of control graph, append the edge to execution path

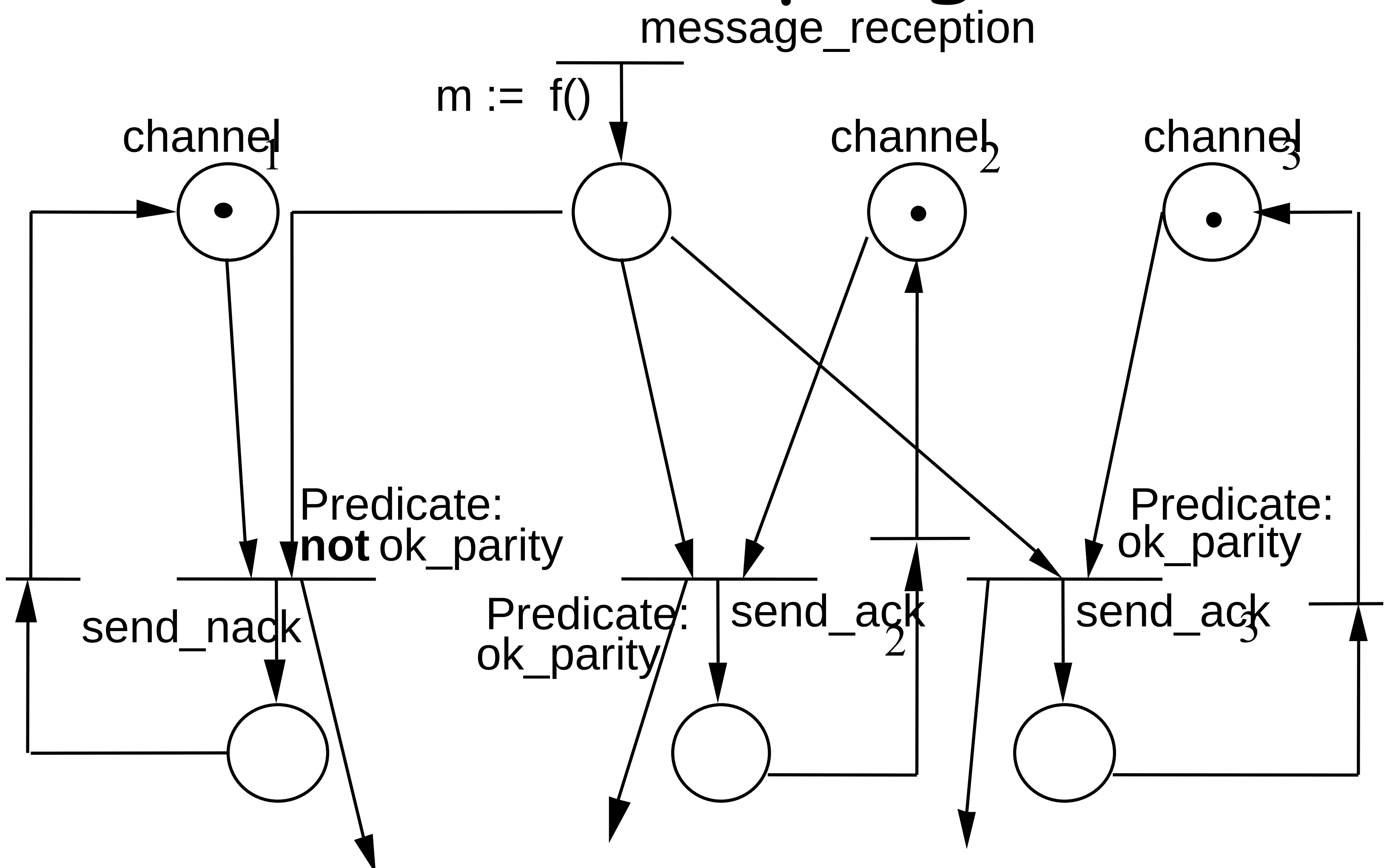
Symbolic execution rules (3)

- if cond then S1; else S2; endif
- while cond loop…endloop
  - condition is symbolically evaluated
    - eval (cond)
  - if eval (cond) $\Rightarrow$ true or false then execution proceeds by following the appropriate branch
  - otherwise, make nondeterministic choice of true or false, and conjoin eval (cond) (resp., not eval (cond)) to the path condition

Programs with arrays

- Let A1 be the symbolic value of array a when statement a(i)= exp is executed
- Then, after execution of the statement, a receives the new symbolic value A2, denoted as A2 = A1<i, exp>, a shorthand for
  - for all k if k = i then A2(k) = exp
    else A2(k) = A1(k)

Symbolic execution of concurrent programs



Assumptions

- Simplifying assumption: no more than one token in a place
- A sequence of atomic steps can be modeled by a firing sequence
  - this resolves the nondeterminism that is due to several transitions being enabled
- The triple <symbolic_variable_values, execution_path, path_condition> can be used to model the symbolic state of the interpreter (execution_path is the firing sequence)

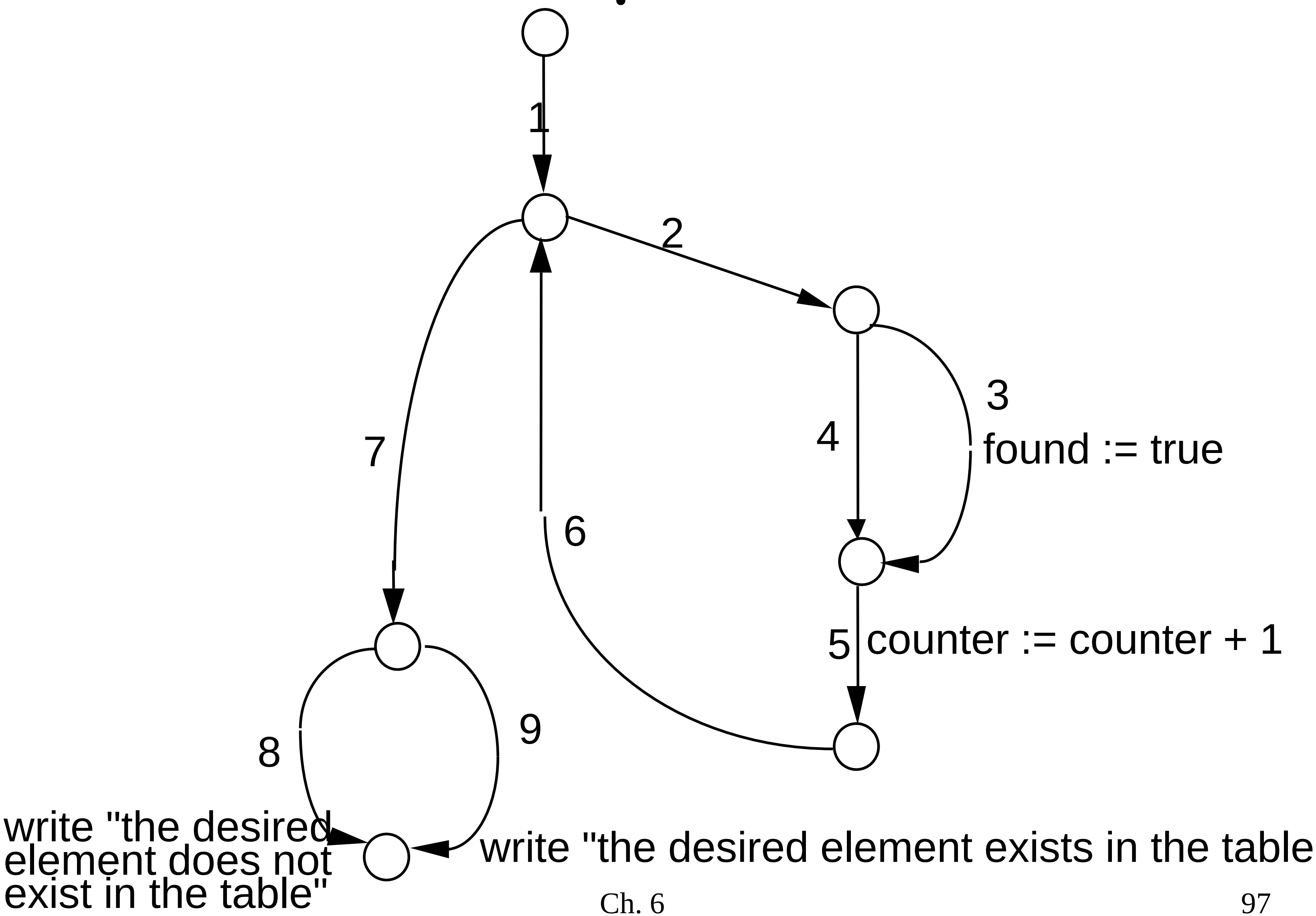
Symbolic execution and testing

- The path condition describes the data that traverse a certain path
- Use in testing:
  - – select path
  - – symbolically execute it
  - – synthesize data that satisfy the path condition
    - they will execute that path

Example (1)

```
found := false; counter := 1;
while (not found) and counter < number_of_items loop
        if table (counter) = desired_element then
                found := true;
        end if;
        counter := counter + 1;
end loop;
if found then
        write ("the desired element exists in the table");
else
        write ("the desired element does not exist
                                        in the table");
end if;
```

Example (2)


1
2
3
found := true
4
5
counter := counter + 1
6
7
8
9
write "the desired element does not exist in the table"
write "the desired element exists in the table"

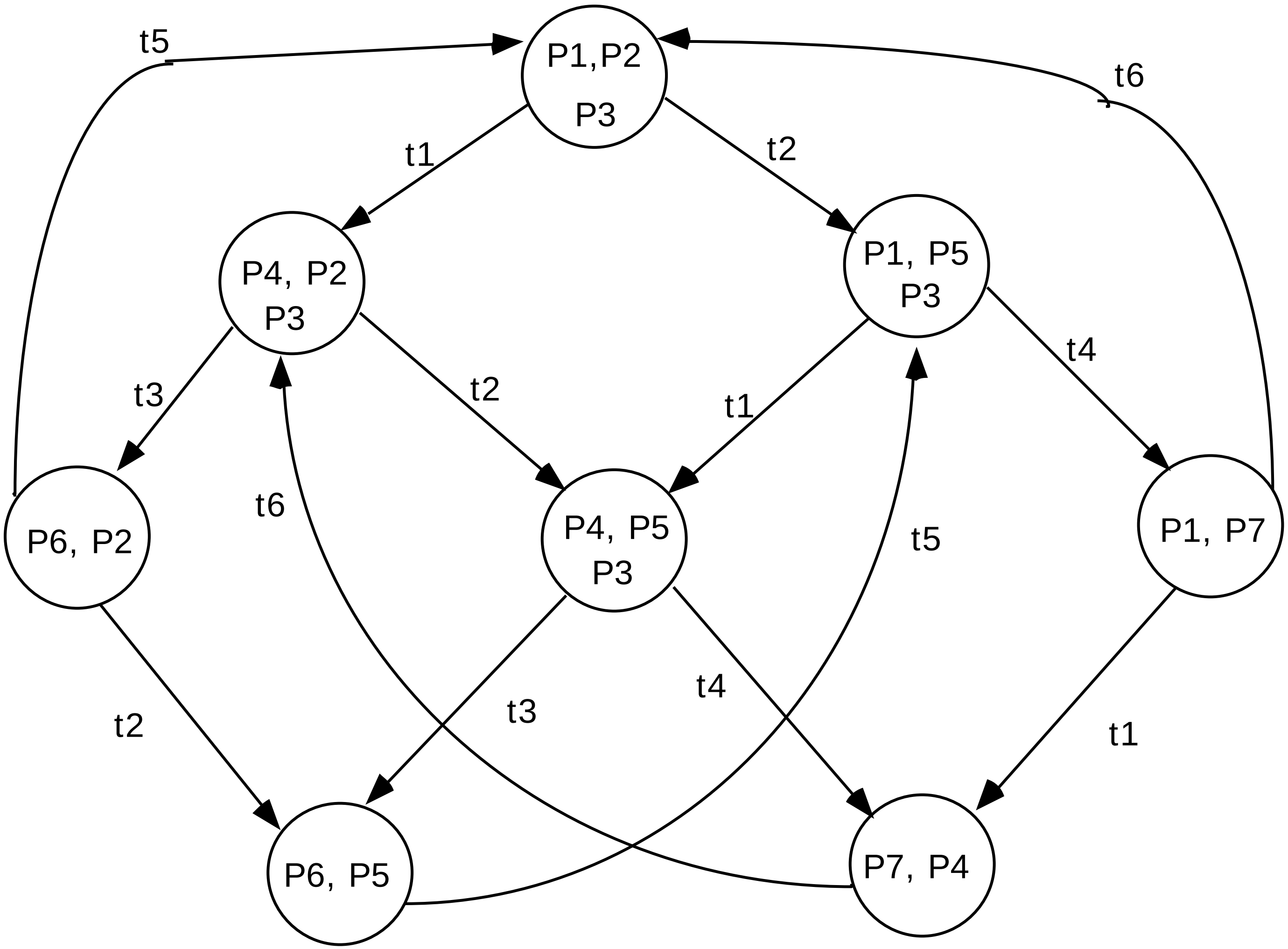
Model checking

- Correctness verification, in general, is an undecidable problem
- Model checking is a rather recent verification technique based on the fact that most interesting system properties become decidable (i.e., algorithmically verifiable) when the system is modeled as a finite state machine

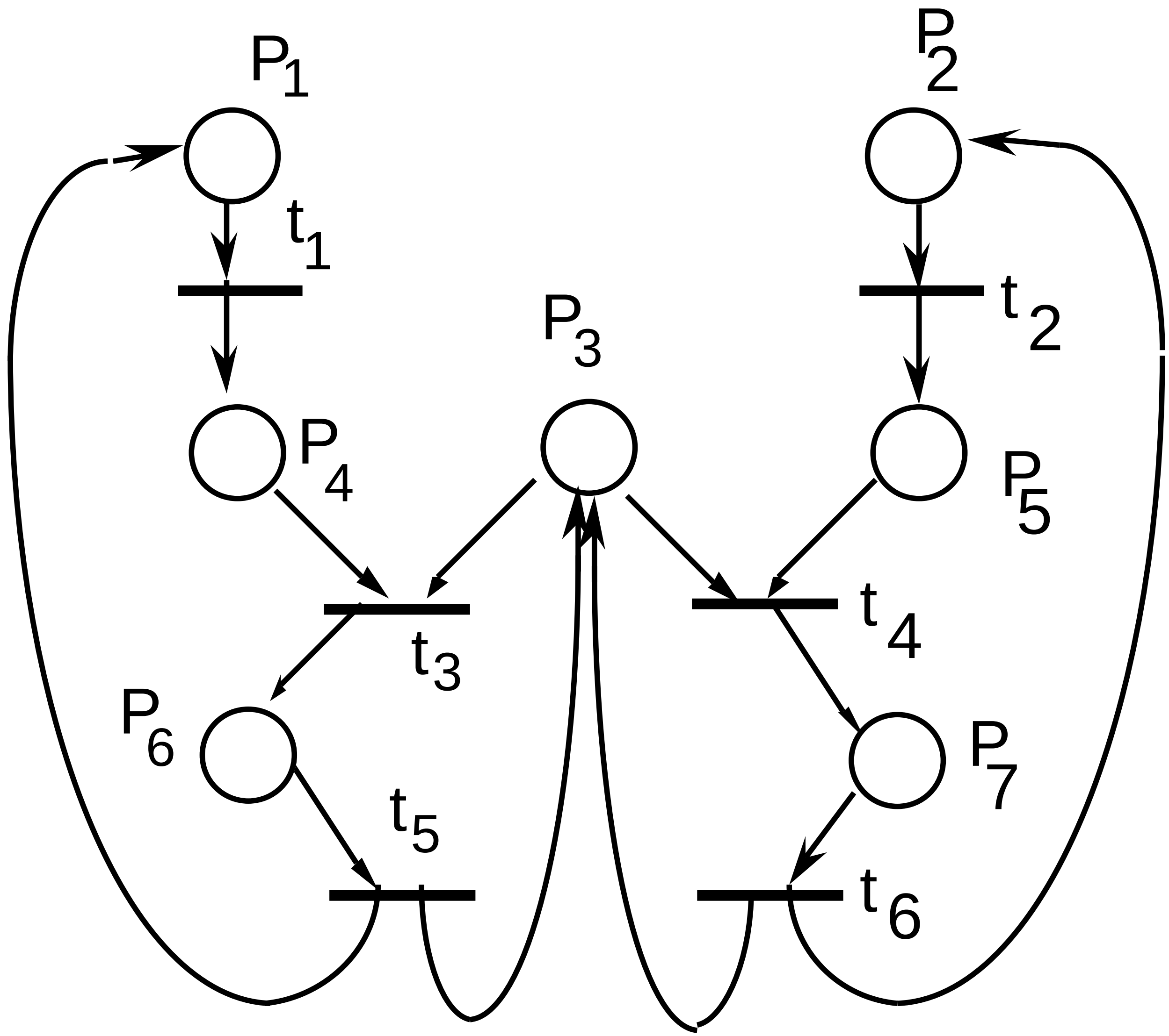
Principles

- Describe a given system—software or otherwise—as an FSM
- Express a given property of interest as a suitable formula
- Verify whether the system's behavior does indeed satisfy the desired property
  - this step can be performed automatically
  - the model checker either provides a *proof* that the property holds or gives a *counterexample* in the form of a test case that exposes the system's failure to behave according to the property

FSM representing markings of a PN



The original PN



Properties and proofs

- Property to be verified given through a formula (in temporal logic)
- In the example, one can prove
  - there is always a computation that allows the left process to enter the critical region
  - there is no guarantee that the left process accesses the shared resource unless it already owns it

Why so many approaches to testing and analysis?

- Testing versus (correctness) analysis
- Formal versus informal techniques
- White-box versus black-box techniques
- Techniques in the small/large
- Fully automatic vs. semiautomatic techniques (for undecidable properties)
- …

view all these as complementary

Debugging

- The activity of locating and correcting errors
- It can start once a failure has been detected
- The goal is closing up the gap between a fault and failure
  - memory dumps, watch points
  - intermediate assertions can help

Verifying other qualities

Performance

- Worst case analysis
  - focus is on proving that the system response time is bounded by some function of the external requests

  vs. average behavior
- Standard deviation
- Analytical vs. experimental approaches

Reliability (1)

- There are approaches to measuring reliability on a probabilistic basis, as in other engineering fields
- Unfortunately there are some difficulties with this approach
- Independence of failures does not hold for software

Reliability (2)

- Reliability is concerned with measuring the probability of the occurrence of failure
- Meaningful parameters include:
  - average total number of failures observed at time t: AF(t)
  - failure intensity: FI(t)=AF'(t)
  - mean time to failure at time t: MTTF(t)=1/FI(t)
- Time in the model can be execution or clock or calendar time

Basic reliability model

- Assumes that the decrement per failure experienced (i.e., the derivative with respect to the number of detected failures) of the failure intensity function is constant
  - i.e., FI is a function of AF

$$FI(AF) = FI_0\,(1 - AF/AF_\infty)$$

  where FI_0 is the initial failure intensity and AF_∞ is the total number of failures
- The model is based on optimistic hypothesis that a decrease in failures is due to the fixing of the errors that were sources of failures

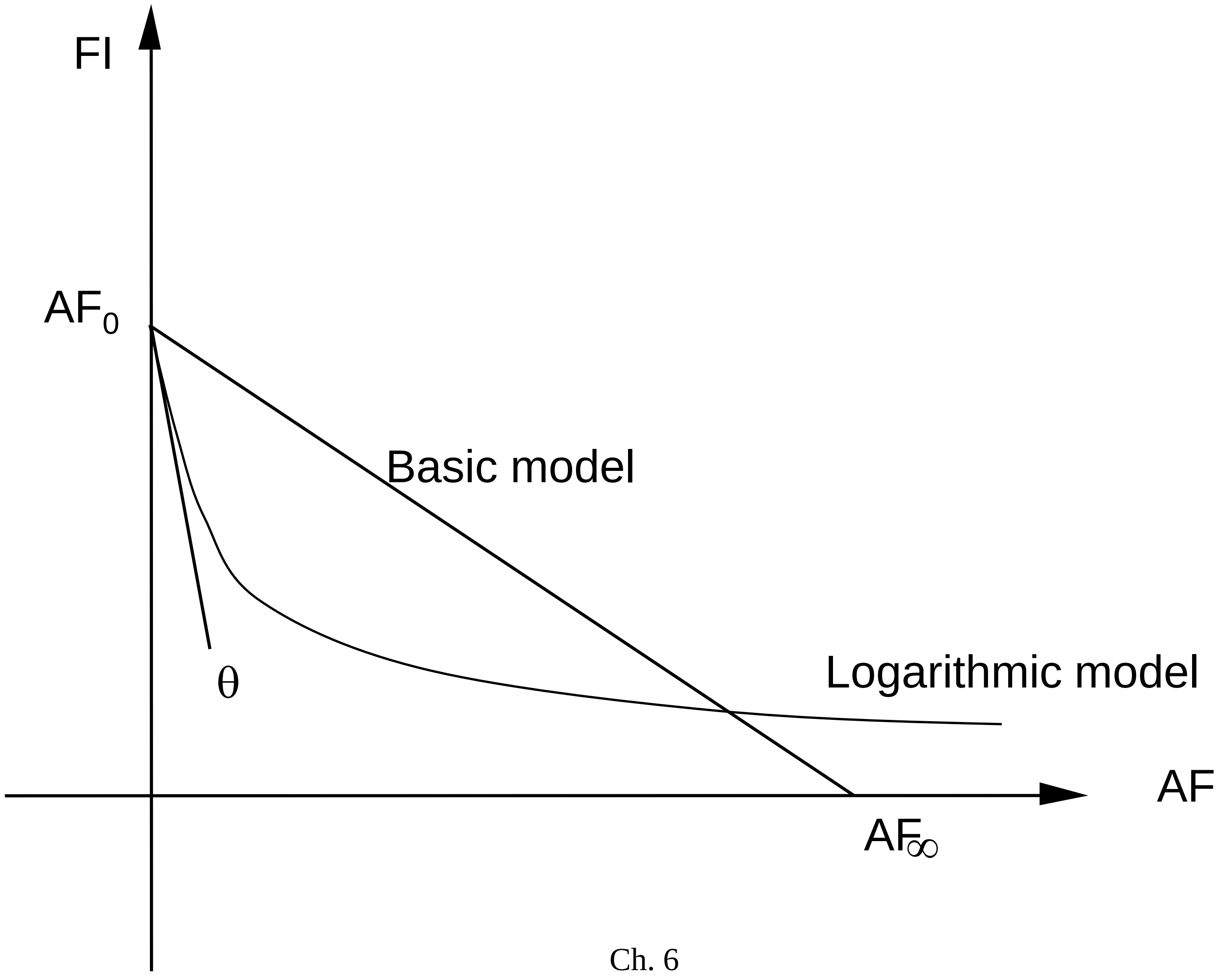
Logarithmic model

- Assumes, more conservatively, that the decrement per failure of FI decreases exponentially

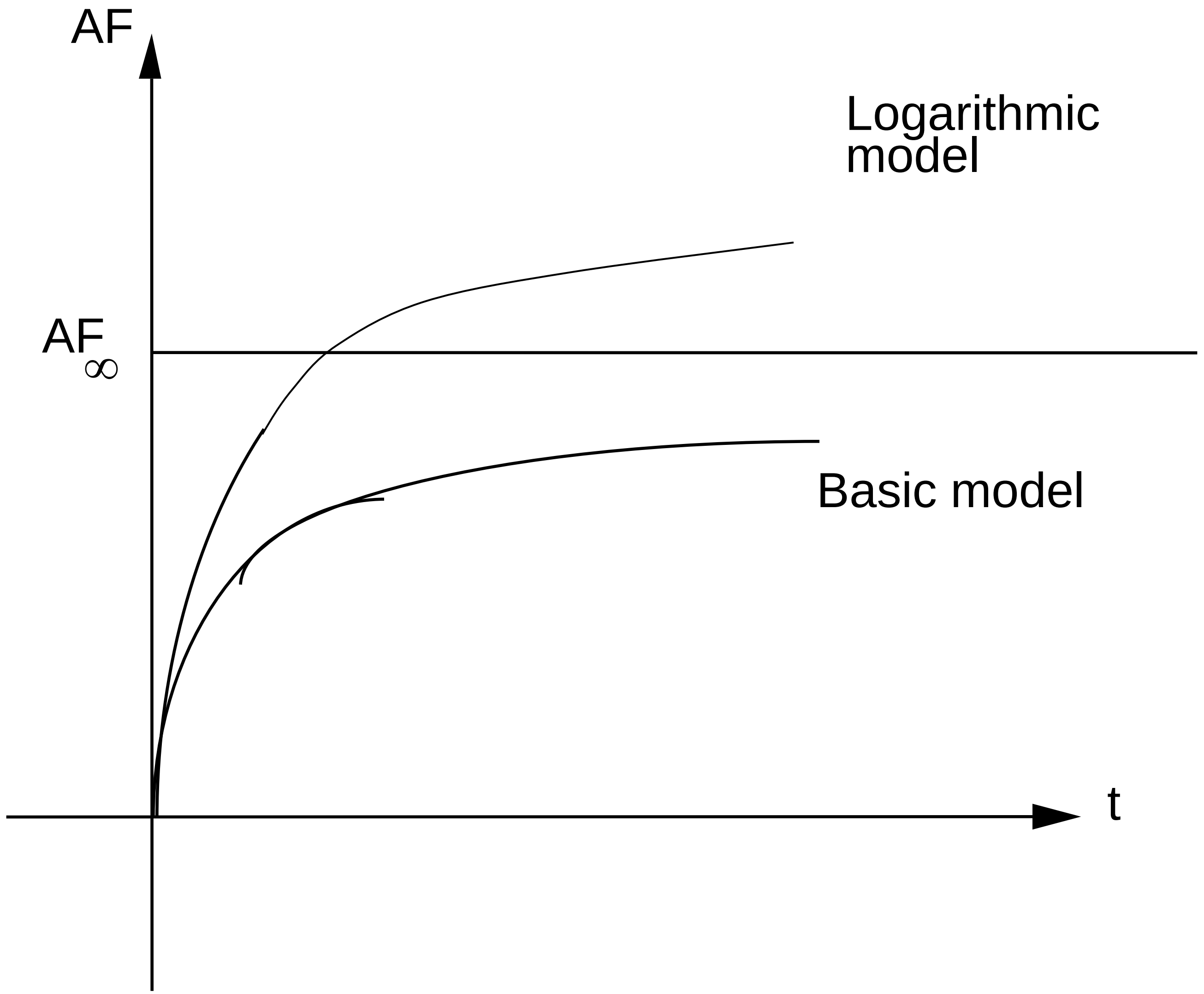
  $FI(AF) = FI_0 \exp(-\theta\, AF)$

  θ: failure intensity decay parameter

Model comparison



Model comparison



Verifying subjective qualities

- Consider notions like simplicity, reusability, understandability …
- Software science (due to Halstead) has been an attempt

Halstead's software science

- Tries to measure some software qualities, such as
  abstraction level, effort, …
- by measuring some quantities on code, such as
  - $\eta 1$, number of distinct operators in the program
  - $\eta 2$, number of distinct operands in the program
  - N1, number of occurrences of operators in the program
  - N2, number of occurrences of operands in the program

McCabe's source code metric

- Cyclomatic complexity of the control graph
  - $C = e - n + 2p$
    - e is # edges, n is # nodes, p is # connected components
- McCabe contends that well-structured modules have C in range 3 .. 7, and C = 10 is a reasonable upper limit for the complexity of a single module
  - confirmed by empirical evidence

Goal-question-metric (GQM)

- Premise
  - software metrics must be used to analyze software qualities, not to evaluate people
  - quality evaluation must be of end product, intermediate products, and process
  - metrics must be defined in the context of a complete and well-designed quality improvement paradigm (QIP)

GQM

- Not concerned with measuring a single quantity or group of quantities
  - e.g., cyclomatic complexity
- A method that is intended to lead from a precise definition of the objectives of measuring qualities (the *goals*) to the quantities (the *metrics*) whose measures are used to verify the achievement of such qualities.

The method

- Define goal precisely—Example:
  - *Analyze* the information system *with the purpose of* estimating *the* costs *from the point of view of* the manager *in the context of* a major software house
- Define suitable set of *questions* aimed at achieving the stated goal
- Associate a precise *metric* with every question