Vorlesung "Spezielle Themen der Softwaretechnik"

# The Cleanroom Method

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- Principles
- Empirical results
- Typical practices
- Stepwise refinement
  - box structures, verification
- Statistical testing
  - Usage modeling
- Cleanroom and CMMI

# Cleanroom classification and goals

- Proposed by Harlan D. Mills, IBM, since 1980
  - 'Cleanroom' stands for defect prevention instead of defect elimination

Goal:

- High, quantified reliability at low cost

Harlan Mills

Classification:

- Cleanroom is a development approach
- and a management approach

Context:

- Whenever precise specifications can be written early
  - For new development, maintenance, and reengineering
  - Independent of language and technology
- Requires approximately CMM Level 3

# Cleanroom principles

Cleanroom development principle:

- Development teams strive to produce products without any defects
  - by careful design and development
  - by verification and review
  - but *not* by testing

Cleanroom testing principle:

- The purpose of testing is measuring the reliability of the product
  - not improving the reliability

Cleanroom management principle:

- Team-based practices limit the scope of human fallability and allow for continuous improvement

# Empirical results: IBM Cobol SF

Freie Universität Berlin

- R.C. Linger, H.D. Mills: *"A Case Study in Cleanroom Software Engineering: The IBM COBOL Structuring Facility",*
  - *12th Intl. Computer Science and Applications Conf.*, Oct. 1988.

- Project developing "Cobol Structuring Facility" COBOL/SF
  - A program analyzer/translator (written in PL/1) for converting Cobol code with GOTOs into structured Cobol code
  - 52 KLOC modified/added to existing 40 KLOC base product
- Overall productivity: +400%
- Overall defect density: 3.4 defects/KLOC
- Field-testing defects: 10 (only 1 of them major)

- The defect reduction is the main reason for the huge improvement in productivity
  - Testing such a system is very laborious

# Empirical results: Ellemtel/Ericsson OS32

Freie Universität Berlin

- L.G. Tann: *"OS32 and Cleanroom"*
  - *1st Annual European Industrial Symposium on Cleanroom Software Engineering, Copenhagen*, Denmark, 1993, pp. 1-40.

- Project developing an operating system for telephone switching systems
  - 73 people staff, 33 months duration
  - 350 KLOC resulting software size (14 LOC/PM)
- Development productivity: +70%
- Testing productivity: +100% (tests per hour)
- Testing defect density: 1 defect/KLOC

- These are very big improvements, considering this was a mature development organization already.

# Empirical results: Controlled experiment



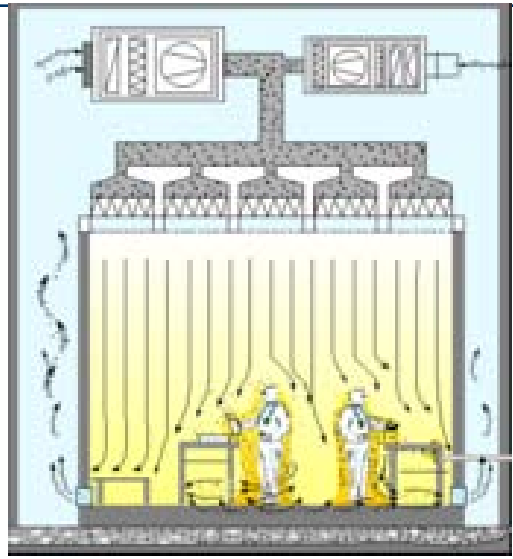
- R. Selby, V. Basili, F. Baker: *"Cleanroom Software Development: An Empirical Evaluation"*
  - IEEE Transactions on Software Engineering, 13(9), Sept. 1987
- A controlled experiment:
  15 teams (10 Cleanroom, 5 conventional) of 3 student developers (w. prof. experience). Each develops the same SW
  - electronic messaging system: duration 6 weeks, 4 milestones,
  - resulting size 800 to 2300 LOC of Simple-T code
- Results:
  - The Cleanroom teams developed more functionality
  - All Cleanroom teams kept all milestones, only 2 of the 5 others did
  - The Cleanroom programs were less complex (control flow) and had better annotation
  - The Cleanroom programs had significantly fewer test failures
  - 86% of the developers missed testing (quality was not affected)

# Typical Cleanroom techniques



Small teams

- High motivation, close cooperation, efficiency
  - **"Defects are not acceptable!"**
- Parallel development
  - Strict modularization has to be done at specification time
- Exact specification
  - All partial specifications are precise and self-contained



Physical cleanroom

Strict separation of development and testing

- Development teams
  - Development teams are strictly forbidden to perform any testing
- Test teams
  - Test teams never modify programs

# Typical Cleanroom techniques (2)

Exact specification

- Defect prevention
  - Precise specifications help avoid ambiguity defects
- Verification
  - During development, defects are continually searched for by comparing with specification
- Z, VDM, box method, special grammars

Stepwise refinement

- Specification (black box)
  - Describes WHAT without HOW
- State description (state box)
  - Specification as a state machine (not always useful)
- Process description (clear box)
  - Partial HOW: "Implementation", but may use further black boxes

# Typical Cleanroom techniques (3)

Review/verification

- Performed for each refinement
  - State box and clear box
- Grounded in mathematics
  - Convincing argumentation, rarely formal mathematical proof
- Argument is formulated and verified during an inspection

Incremental development

- Initially, only basic functionality is developed

Statistical testing

- Usage modelling
  - Test cases are a random sample according to usage model
- Quantitative statement on reliability (certification)

# Typical Cleanroom techniques: Note



- First and foremost, Cleanroom development is an attitude
  - So none of the above techniques is absolutely mandatory:

They can be driven to extremes

- for instance developers may be prohibited to even compile their code

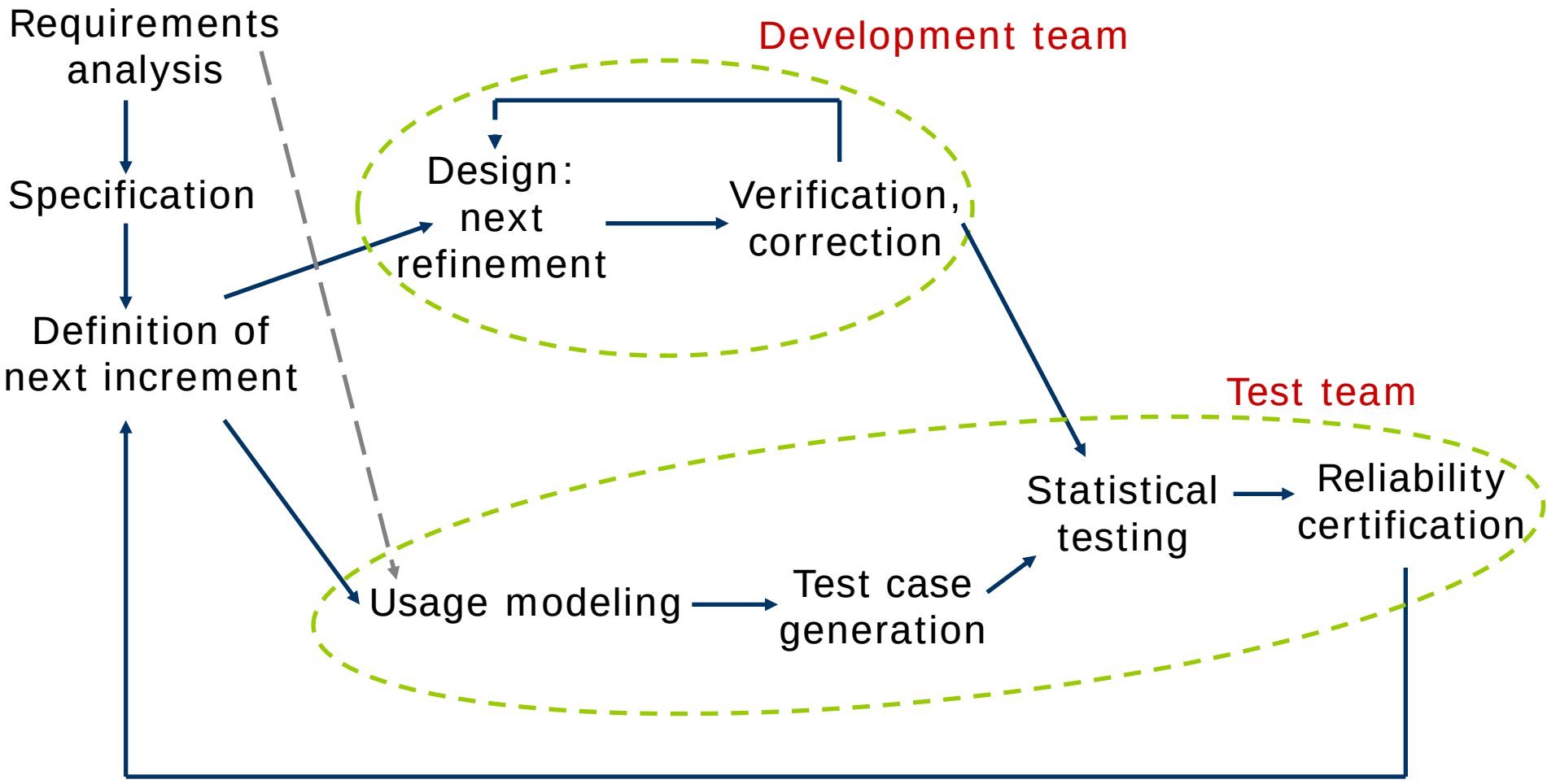
They can be relaxed

- for instance by performing defect testing before statistical testing

They can be exchanged for others

- for instance by driving development in some other way than by box refinement

# Cleanroom process flow overview



# Problems and Obstacles



Cleanroom is not suited if

- ...formal specification is difficult
  - which is commonly the case for interactive systems
- ...determining the correctness of test outputs is costly
  - but this is a problem for conventional development as well.
  - One could still do Cleanroom without reliability certification
    - leave out statistical testing

Necessary preconditions:

- Highly trained software engineers
  - Others cannot create reliable verification arguments
- Defined software process (CMM Level 2/3)
  - Immature processes will lack the necessary discipline and control

# Specification and design with box structure

- Define black box:
  - define output based on input history
- Define state box:
  - define states for the representation of input history
  - reformulate black box (may introduce several new black boxes)
  - verify reformulation: state box must be equivalent to black box
- Define clear box:
  - define data abstraction for state data
  - reformulate state box
    (may introduce several new black boxes)
  - verify reformulation:
    clear box must be equivalent to state box

Continue with black boxes of the refinement

# Trivial refinement example

- *black box 1:* triangleType(a, b, c)

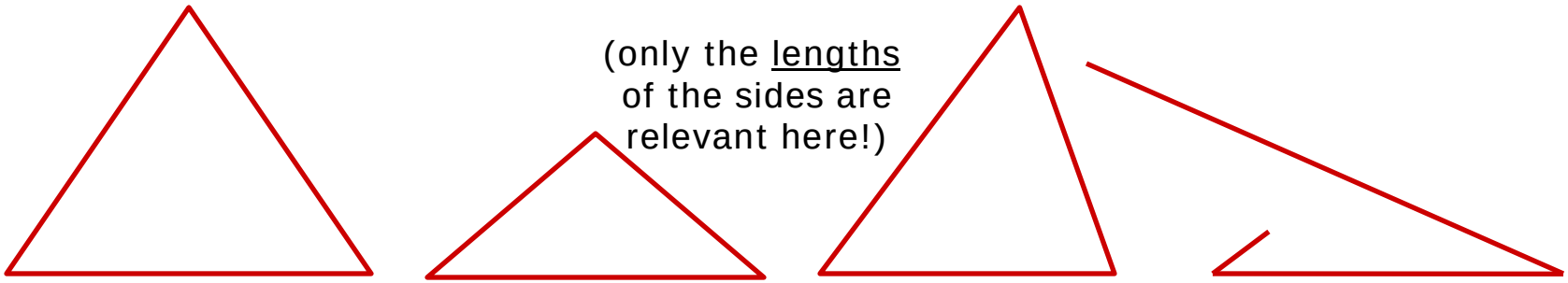
*precondition:* a, b, c are positive, real numbers

*postcondition:*

return EQUILATERAL / ISOSCELES / OTHER / NO_TRIANGLE

⇔

the triple (a, b, c) is side lengths of an equilateral / non equilateral isosceles / non isosceles triangle / cannot be side lengths of a triangle



# Refinement example (2)

- *clear box 1:* triangleType(a, b, c)

IF allSidesSatisfyTriangleInequation(a, b, c)
THEN return trueTriangleType(a, b, c)
ELSE return NO_TRIANGLE

- *black box 2:* allSidesSatisfyTriangleInequation(a, b, c)

precondition: a, b, c positive, real numbers
postcondition: True if each side is shorter than the sum of the other two; else False

- *black box 3:* trueTriangleType(a, b, c)

precondition: (a, b, c) are the side lengths of a triangle
postcondition: ...

# Refinement example (3)



- *verification clear box 1:*

(a, b, c) can form triangle ⇔

the two shorter sides x, y together are longer than the longest, z.

Hence, z < x + y (i.e., "side z satisfies triangle inequation") is sufficient for diagnosing a triangle.

"All sides satisfy triangle inequation" is a stronger condition, hence also sufficient.

Hence, clear box 1 is correct.

(Note: The argument is simplified.
It does not cover the necessity of the conditions.)

# Refinement example (4)

- *clear box 2:* allSidesSatisfyTriangleInequation(a, b, c)

return (a < b + c AND b < a + c AND c < a + b)

- *verification clear box 2:*

3 different side lengths a, b, c are tested (→ "triangle"),
tests are connected by 'AND' (→ "all sides"),
each test compares one side to the sum of the two others,
each comparison is by 'less than' (→ correct inequation).
Hence, the implementation appears to be correct

# Refinement example (5)

- *clear box 3:* trueTriangleType(a, b, c)

IF a = b= c THEN return EQUILATERAL

ELSE IF a = b OR a = c OR b = c THEN return ISOSCELES

ELSE return OTHER

- *verification clear box 3:*

'Equilateral' is a special case of 'isoceles' and must therefore be tested first, this is done here.

The test for 'equilateral' is correct.

The test for 'isosceles' must check 3 different pairs (correct), only one needs to be equal (connection with 'OR', correct)

'Other' is the only remaining case, must be 'ELSE' part. Correct.

Therefore clear box 3 is correct.

# Statistical Testing and Certification



- Most software processes use defect testing
  - Goal: Find as many defects as possible, with as few test cases as possible
  - Testing concentrates on 'difficult' cases.
- Defect testing makes almost no statement about reliability.

- In contrast, Cleanroom uses statistical testing
  - Goal: Quantify reliability, somewhat like acceptance testing
  - Does not specifically aim to find defects
  - Testing reflects typical frequencies of typical cases

- Basis: Usage modelling
  - Based on description of the usage profile (from requirements)
  - Mathematical description with Markov-chains (finite state space, discrete events)

# Example: Excerpt from the usage model for a text editor

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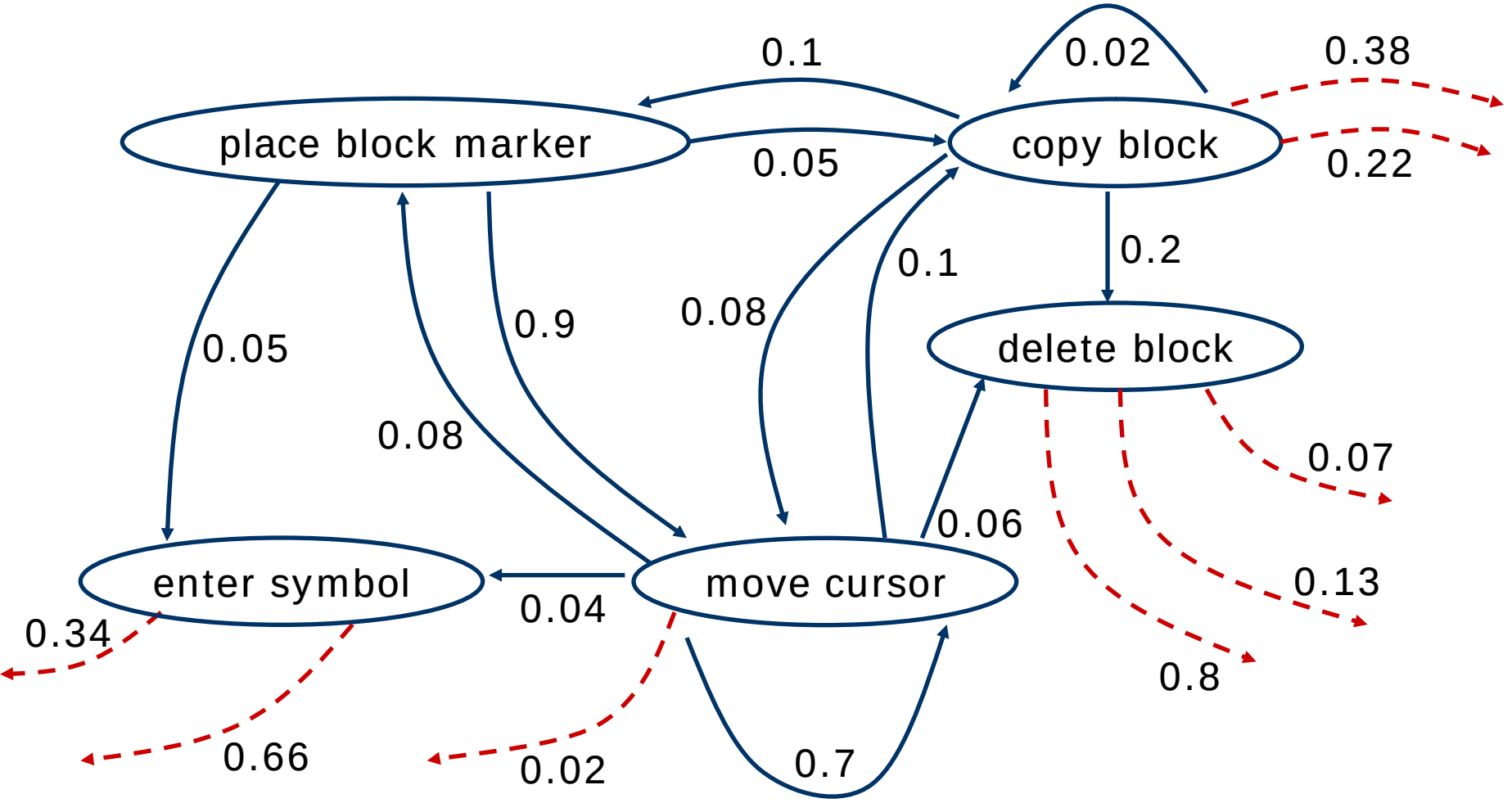
Probabilistic state machine: States are actions, stochastic sequencing



# Testing process



- Any number of test inputs can be generated automatically
  - based on the usage model
- Output correctness predicate?
  - Depends on application
  - Often only plausibility checking is possible
- Measure the intervals between failures
  - Terminate when sufficient reliability can be certified
  - Stop when insufficient reliability has been determined

# Reliability certification



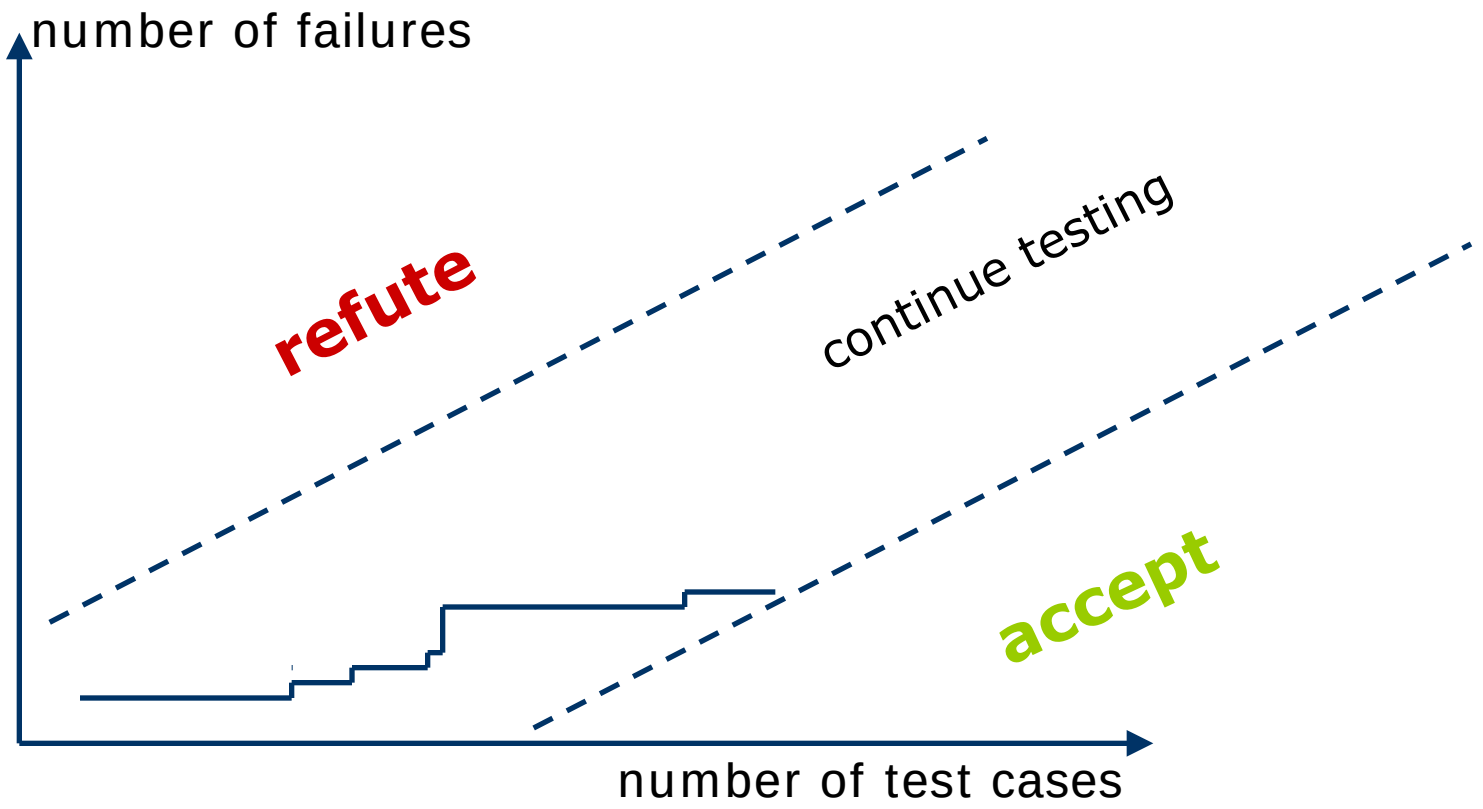
- The goal is a statement such as
  "MTTF(program) ≥ m with confidence K"
  - e.g. "With confidence 95% we can say that this program fails at most once every 2 000 000 steps"
  - MTTF: mean time-to-failure

- Computed with statistical methods (binomial distribution)

- Problem:
  When I find and correct a defect,
  may I still use the data from the previous test runs?
  - Defect models and reliability models may allow this,
  - but then need to rely on assumptions (in particular the non-introduction of new failures).
  - This is beyond the scope of this lecture.

# Certification testing: basic idea

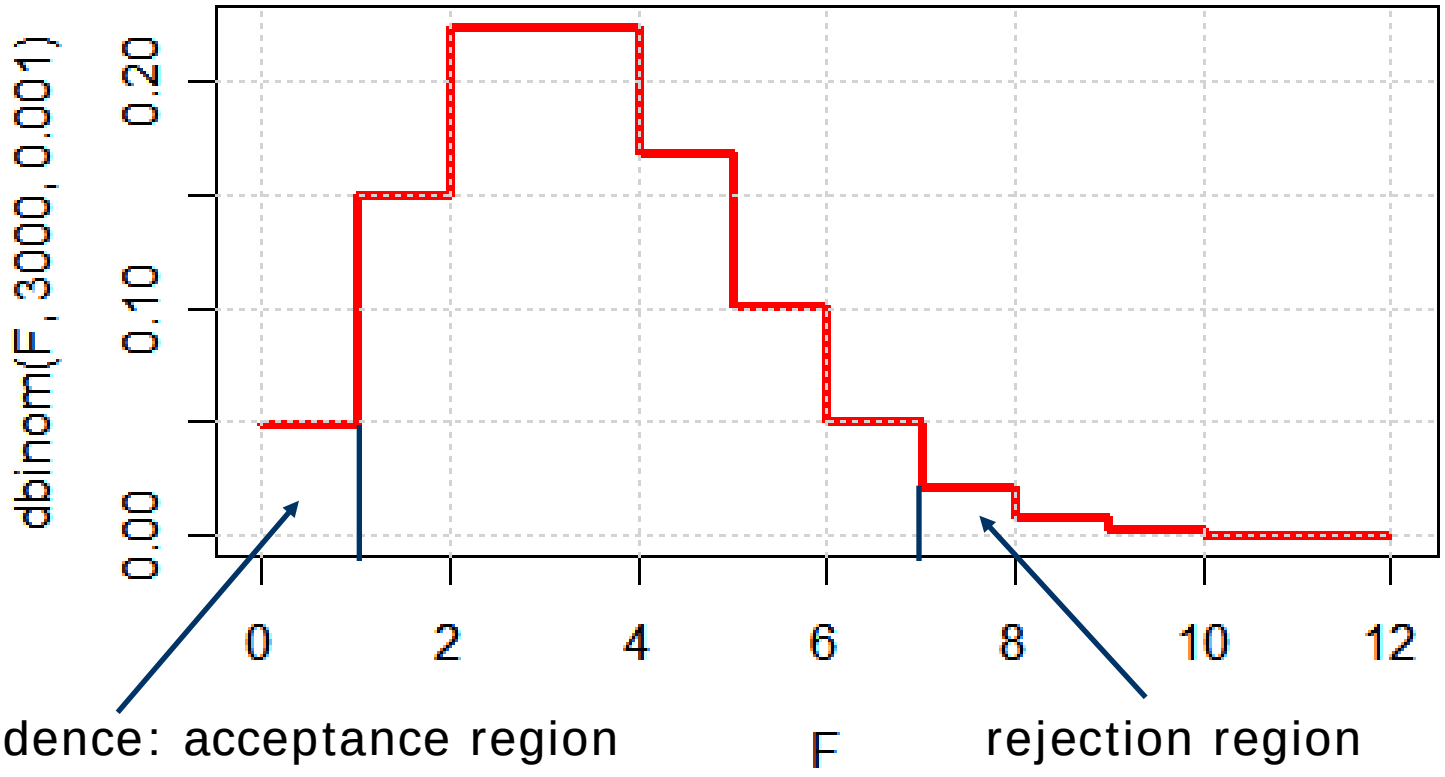
Schematic view! Details follow




Note that the up-steps are not vertical; they go 1 to the right as well.

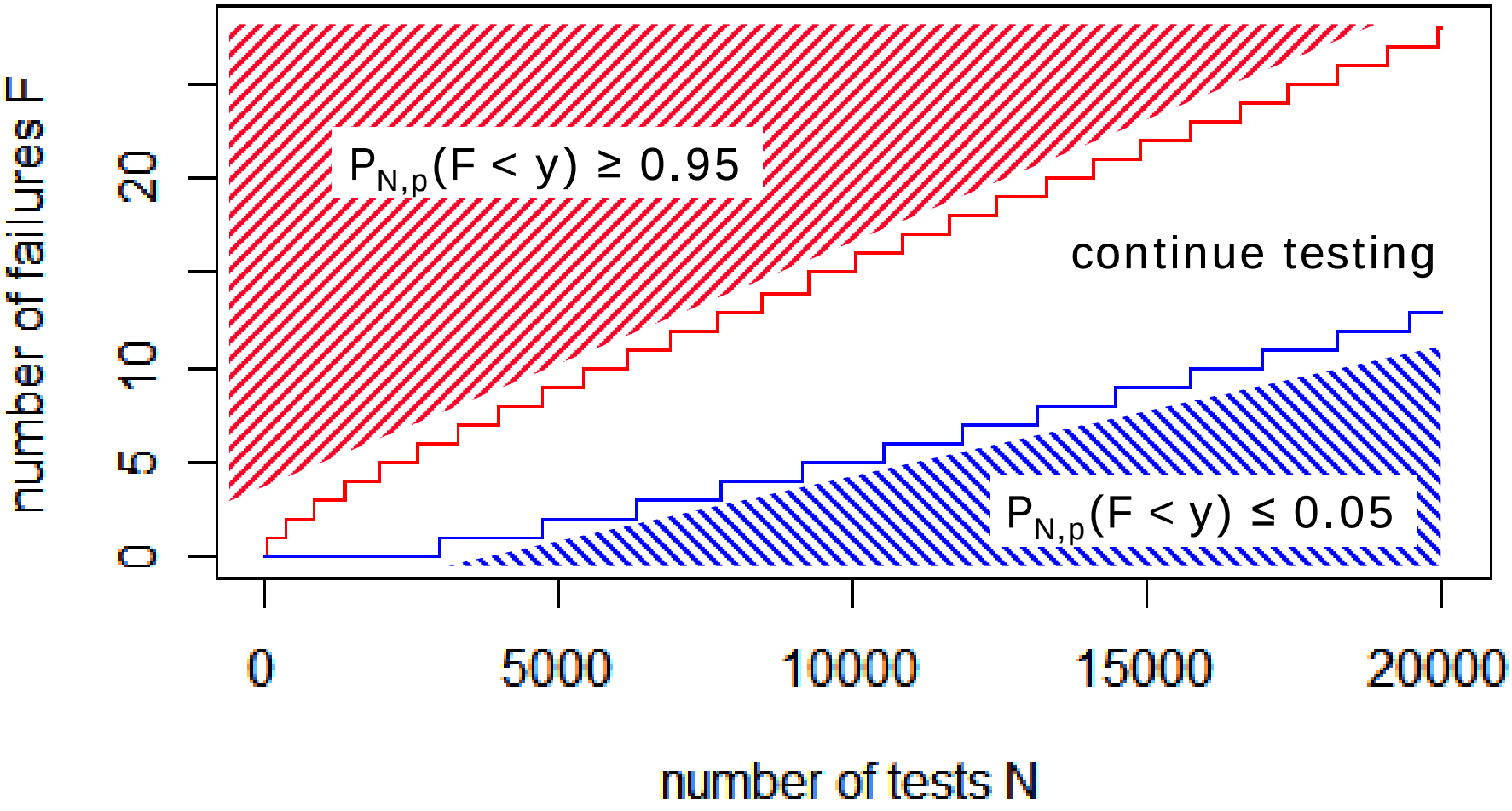
# Details: Binomial distribution

- Given an event (here: failure) with probability p (here: 0.001)
  - i.e. we want to certify 99.9% reliability (= 1-p)
- A binomial distribution describes the number F of failures to be expected during N runs (here: N=3000)



# Certification testing

- Limit lines for binomial distribution (N trials, p=0.001)



# Cleanroom and CMMI



- CMMI process areas covered by typical Cleanroom practices

- Level 2: Managed
  - Measurement and Analysis MA
    - with respect to reliability only
  - Process and Product Quality Assurance PPQA
    - verification discipline

- Level 3: Defined
  - Technical Solution TS
    - SP 2.3 Design Interfaces Using Criteria: formal specification
  - Verification VER
    - The heart of Cleanroom!

- Level 4: Quantitatively Manag'd
  - Quantitative Project Mgmt QPM
    - Statistical testing

- Level 5: Optimizing

# Cleanroom and CMMI (2)



- Cleanroom alone does not get you anywhere wrt. CMMI
  - not even to Level 2

- But the quality culture inspired by Cleanroom was found a useful driver for many improvements up to Level 5:
  - Level 2: PPQA (developers become process-quality-aware);
  - Level 3: VER (reviews become standard practice)
  - Level 4: OPP (defect densities become a natural process benchmark)
  - Level 4: QPM (quantitative quality management is established)
  - Level 5: OID (developers start continuous improvements wrt. defect avoidance, thus opening the organization for process improvement)

# Summary: Cleanroom Software Engineering



- Do not accept defects, favor defect prevention over detection

- Exact specification
- Stepwise refinement with box-specification
- Verification during inspection

- Statistical testing based on usage model
- Reliability certification

- Result: very low defect rate, high productivity

# Further sources

CleanSoft is a US company specializing in Cleanroom:

- http://www.cleansoft.com/cleansoft_bibliography.html
  - A list of important published works on Cleanroom Software Engineering
- http://www.cleansoft.com/cleansoft_library.html
  - Several nice overview articles by members of CleanSoft

# Thank you!