Software Quality Engineering:

Testing, Quality Assurance, and Quantifiable Improvement

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Chapter 10. Coverage and Usage Testing Based on FSMs and Markov Chains

- Finite-State Machines (FSMs)
- FSM-Based Testing
- Markov Chains as Enhanced FSMs
- Unified Markov Models for Testing

Alternative Testing Models

- Motivation: Why FSMs?
  - ▷ Complicated operations involve many steps/stages in the end-to-end chain
  - ▷ Not modeled in checklists/partitions.
  - ▷ Ability to use existing models and structural information
  - ▷ Ability to use localized knowledge
  - ▷ Local information easy to gather

- FSM: Basic ideas
  - ▷ State: operations/functions.
  - ▷ Transition: link in a chain.
  - ▷ Input/output associated with transition.
  - ▷ Complete operation: chain.

FSMs as Graphs

- FSMs often represented by graphs.

- State/node and properties:
  - ▷ Represents status/processing/component
  - ▷ Identification and labeling
  - ▷ Other properties: node weights

- Links and link properties:
  - ▷ Represent state transitions.
  - ▷ Labeling: Often by the nodes they link.
  - ▷ Other properties: link weights
    – associated input and output.
  - ▷ Directed (e.g., A-B link $\neq$ B-A link).

Types of FSMs

- Types of FSMs:
  - ▷ Classification by input/output.
  - ▷ Classification by state.
  - ▷ Other classifications possible.
- FSM types by input/output representation:
  - ▷ Mealy model: both input and output associated with transitions
  - ▷ Moore model: output represented as separate states.
  - ▷ Mealy model used in this book.

Types of FSMs

- Classification by state representation.
  - ▷ Type I. state = status, with most of the processing and I/O at transition.
  - ▷ Type II. transition = I/O free link, with most of the processing and I/O at state.
  - ▷ We use both, and mixed type too.

- Type I & II as Mealy models:
  - ▷ Type I: classical Mealy model.
  - ▷ Type II: modified Mealy model, I/O not explicitly represented in FSMs.
  - ▷ Mixed type: used for convenience if not leading to confusion.

Types of FSMs

- Type I example: classical Mealy model.
  – also web testing example in Section 10.3.

- States:
  - ▷ "initial" state: when program starts,
  - ▷ "final" state: where program terminates,
  - ▷ other states (and transitions below).

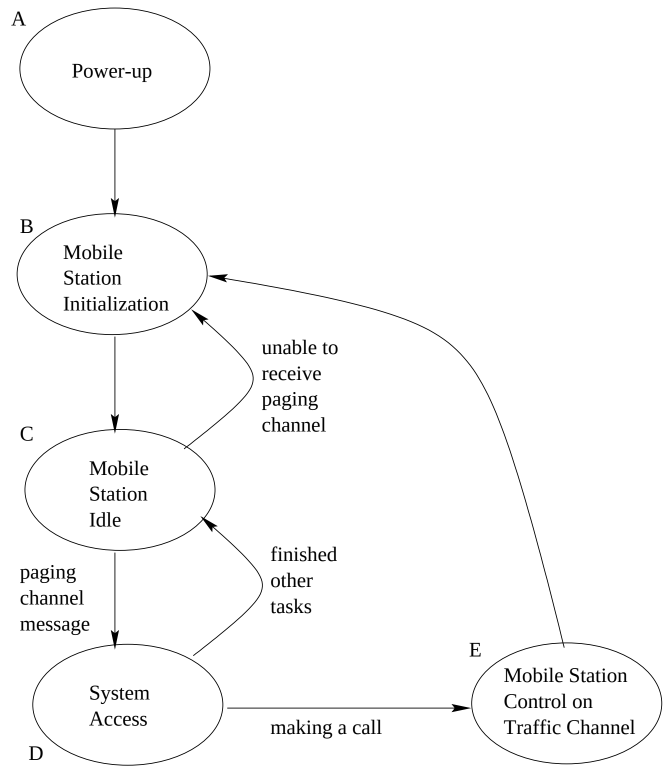
- State transitions accompanied by some processing and associated I/O:
  - ▷ performing user-oriented functions
  - ▷ execution some statements
  - ▷ I/O associated with above (or empty)

Types of FSMs

- Type II example: control flow graph (CFG) or flow chart in Chapter 11.

- Mixed type for convenience:
  - ▷ Hard to restrict to one type $\Rightarrow$ use mixed type.
  - ▷ Ensure no confusion.
  - ▷ Key: significant difference among states so that state transitions are meaningful.

Types of FSMs



- Mixed type example: Fig 10.1 (p.151)
  - ▷ states with processing: A, B, D, E
  - ▷ state w/o processing: C (status)
  - ▷ transitions: implicit or no output
    - – explicit input: C-D, C-B, D-C, D-E.
    - – implicit/no input: A-B, B-C, E-B.

FSM Representation

- FSM as a table/matrix
- Cell (x, y): I/O associated with transition from state x to state y.
  – “na”: transition not allowed.
- Table 10.1 (p.152) for FSM in Fig 10.1.

	A	B	C	D	E
A	na	-/-	na	na	na
B	na	na	-/-	na	na
C	na	NoC/-	na	msg/-	na
D	na	na	done/-	na	call/-
E	na	-/-	na	na	na

FSM/Graph Representation

- Types of graphs:
  - ▷ Directed graph: FSM etc.
  - ▷ Undirected graph: neighbor-relation, etc.
  - ▷ Connectivity vs. disconnected graphs.

- Graph representation:
  - ▷ Graphical: good for human processing (mostly in the book)
  - ▷ Tables/matrices: machine processing
  - ▷ Lists: compact sets of items like {C, B, "unable to receive paging channel", -}
  - ▷ Conversion: easy, but need to know how.

Basic FSM Testing

- Typical problems:
  - ▷ Missing, extra, or incorrect states.
  - ▷ Missing, extra, or incorrect transitions.
  - ▷ Input problems: treat as related state or transition problems.
  - ▷ Output problems: as oracle problems.

- Basic approach:
  - ▷ Missing/extra states/transitions dealt with at FSM construction stage.
  - ▷ Basic coverage: Node and link coverage via state traversal based on graph theory and algorithms.
  - ▷ Assuming correct functioning of individual state ensured by lower level testing.

Basic FSM Testing

- Checking for missing/extra states/links during model construction.

- Model construction steps:
  - ▷ Identify info. sources and collect data.
  - ▷ Construct initial FSM.
  - ▷ Model refinement and validation.

- Identify information sources and collect data.
  - ▷ external functional behavior (black-box):
    – specification, usage scenarios, etc.
  - ▷ internal program execution (white-box):
    – design, code, execution trace, etc.
  - ▷ also existing test cases, documents, etc.
  - ▷ key: linking individual pieces together.

Basic FSM Testing

- Construct initial FSM.
  - ▷ state identification and enumeration (states↑↑ ⇒ nested/hierarchical FSMs)
  - ▷ transition/link identification
  - ▷ identify I/O relations (as test oracles)
  - ▷ key sub-step: link identification

- Link identification and problem detection:
  - ▷ identify all possible input for each state,
  - ▷ input values may be partitioned (Ch. 9)
  - ▷ each partitioned subset/subdomain associated with a state transition
  - ▷ undefined transition for some input ⇒ missing state or extra link identified.
  - ▷ extra state or missing link identified by the collective states and transitions (or by connectivity algorithm later)

Basic FSM Testing

- Model refinement and validation.
  - ▷ Refinement with additional states/links.
  - ▷ State explosion concerns
    – at most "dozens" of states in FSMs
  - ▷ Proper granularity needed
    ⇒ use of nested/hierarchical FSMs

- Applicability:
  - ▷ Suitable for menu driven software.
  - ▷ Systems with clearly identified states/stages.
  - ▷ Interactive mode (many I/O pairs).
  - ▷ Control systems, OOS, etc.

- Key limitation: state explosion!
  ⇒ nested FSMs, or Markov chains (later)

Basic FSM Testing

- Node/link coverage via state traversal
  - ▷ Based on graph theory/algorithms.
  - ▷ States directly covered.
  - ▷ Link coverage: starting from state in combination with input domain testing ideas (Ch.8&9).

- Implementation issues:
  - ▷ Sensitization: easy, with specific input.
  - ▷ State cover: series of links with input.
  - ▷ Capability to "save" state information:
    – help with link coverage from the state,
    – state traversal w/o much repeating.
  - ▷ Oracle: output with link (and destination state too!)

Case Study: FSMs for Web Testing

- Web applications vs. menu-driven systems:
  - ▷ Many similarity but significant differences.
  - ▷ Computation vs. information/document.
  - ▷ Separate vs. merged navigations.
  - ▷ Entry/exit/control difference.
  - ▷ Differences in population size/diversity.
  - ▷ Layers in web applications.

- Web layers: Fig. 10.2 (p.158)

Client – Web Browsers
Web Server
Middleware
Database – Backend

Case Study: FSMs for Web Testing

- Web problems: What to test:
  - ▷ Reliability: failure-free content delivery.
  - ▷ Failure sources identified accordingly:
    - host or network failures
    - browser failures
    - source or content failures
    - user problems
  - ▷ Focus on source/content failures

- Web source/content components:
  - ▷ HTML and other documents
  - ▷ Programs (Java/JavaScript/ActiveX/etc.)
  - ▷ Data forms and backend databases
  - ▷ Multi-media components

FSMs for Web Testing

- Testing of individual components:
  $\approx$ traditional testing (mostly coverage).

- Testing of overall operation:
  - ▷ FSMs for navigation/usage
  - ▷ States = pages
  - ▷ Transitions = embedded links
    (direct URLs not by content providers)
  - ▷ I/O: clicks & info. loading/displaying.

- Difficulty: size!
  $\Rightarrow$ extending FSMs for selective testing.

Markov Usage Model: Overview

- Markov-chain OP models
  - ▷ State transitions and probability
  - ▷ Markov property
  - ▷ Attractive in interactive systems, GUI, and many state-transition types
  - ▷ Structural and conceptual integrity

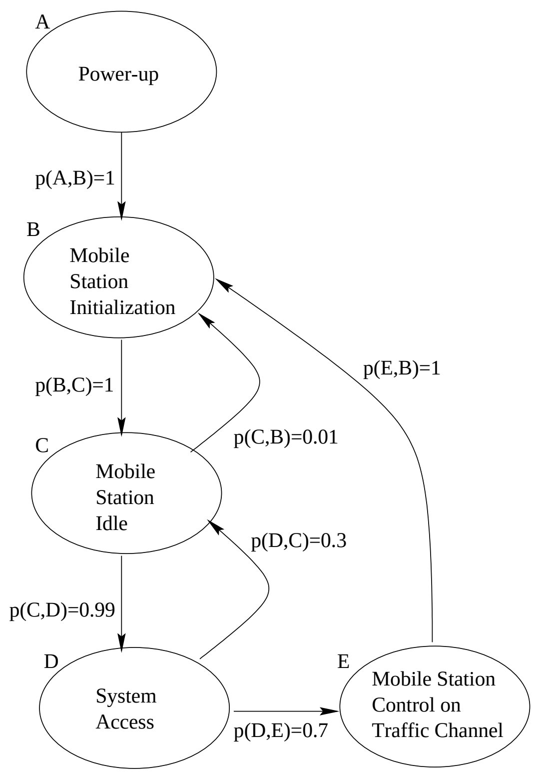
- Comparison with Musa OP:
  - ▷ Similar to FSM vs list/partitions.
  - ▷ Musa OP as collapsed Markov chains.
  - ▷ Coverage: harder to achieve.

Markov Usage Model

- Applications:
  - ▷ Similar to flat OP (Musa), but captures more detailed information
  - ▷ Models functional *structure and usage*
  - ▷ Test case generation more complex
  - ▷ Result: both analytical and observational

- Background and Linkage:
  - ▷ Augmented FSMs.
  - ▷ Cleanroom background: testing technique and tools
  - ▷ (Whittaker and Thomason, 1994) – TSE 20(10):812-824 (10/94)
  - ▷ UMM and web testing at SMU

Markov OP



- Example Markov chains: Fig 10.3 (p.162)

- FSMs with probabilistic state transition p_{ij}, probability from state i to state j
  $0 \leq p_{ij} \leq 1$, and $\sum_j p_{ij} = 1$.

Markov OP and UMMs

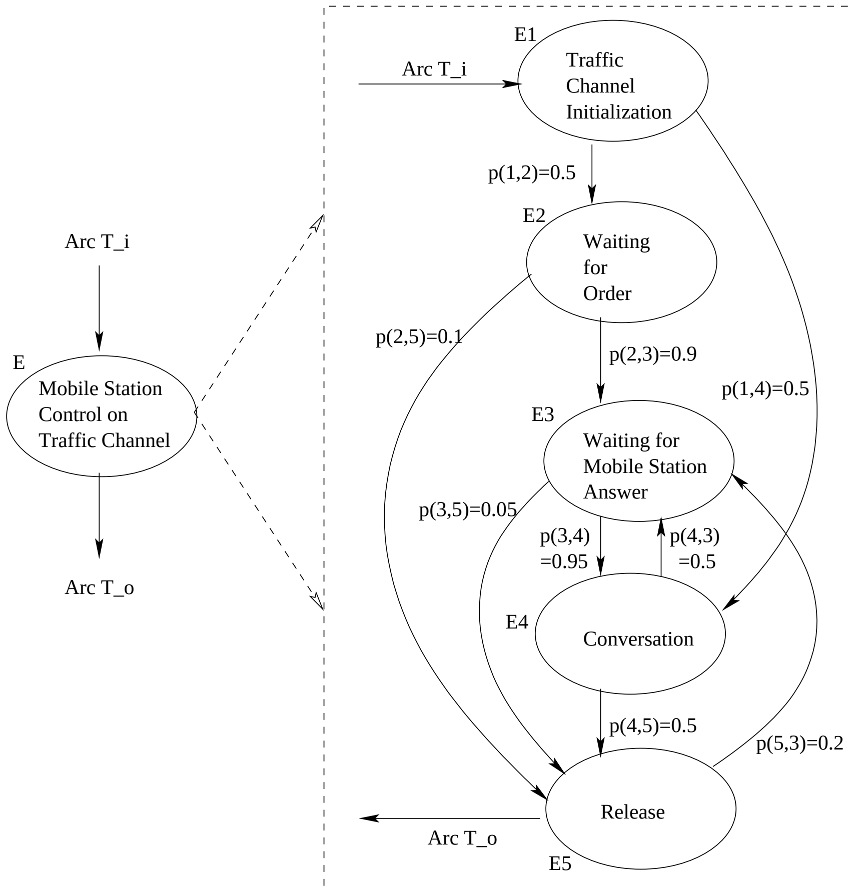
- Memoryless or Markovian property:

$$P\{X_{n+1} = j | X_n = i, X_{n-1} = s_{n-1}, \ldots, X_0 = s_0\}$$
$$= P\{X_{n+1} = j | X_n = i\}$$
$$= p_{ij}.$$

- Markov chain: p_{ij} history independent
  - ▷ most well-studied stochastic process
  - ▷ rich analytical/theoretical results
  - ▷ many applications

- UMM: Unified Markov Models
  - ▷ Hierarchical modeling idea.
  - ▷ Markov chains at different-levels.
  - ▷ More flexibility for statistical testing.

UMM Example



- Example UMM:
  - ▷ Fig 10.3 (p.162): top-level Markov OP
  - ▷ expand state E into Fig 10.4 (p.163) above

Markov/UMM Construction: Steps

- Structure of Markov chain:
  - ▷ State machines:
    e.g., IS-95 call processing ⇒ Fig 10.3
  - ▷ Flow diagram/function description.
  - ▷ At proper granularity
  - ▷ Same as FSM construction earlier

- Transition probabilities:
  - ▷ Various way to obtain
    – measurement/survey/expert-opinion
    – Musa procedures (Ch.8) usable?
  - ▷ May use structural/domain knowledge

- UMM hierarchy determination/adjustment along the way.

Markov/UMM Construction

- Other sources of information:
  - ▷ Sources for FSMs, with emphasis on external/black-box information
  - ▷ Existing flow charts/testing model
  - ▷ Performance models (especially for real time systems)
  - ▷ Analytical (e.g. queuing) models
  - ▷ Market/requirement analyses
  - ▷ Similar/earlier products
  - ▷ Industry standards/external surveys

- Use of the above information sources
  - ▷ for FSMs and transition probabilities
  - ▷ existing hierarchies ⇒ UMM hierarchies?

Markov/UMM Analysis

- Analysis of the chain/model:
  - ▷ Static/stationary properties
  - ▷ Transient properties
  - ▷ Analysis difficulties if size$\uparrow$ or non-stationary process.
  - ▷ Alternative: simulation & measurement.

- Testing result analysis:
  - ▷ Testing using Markov OP
  - ▷ Collect failure data
  - ▷ Fit to reliability models $\Rightarrow$ direct reliability assessment.

Markov/UMM: Testcase Generation

- Basic approaches:
  - ▷ Markov chain ⇒ test cases
  - ▷ Static: off-line, traditional
    - – need more analysis support
  - ▷ Dynamic: on-line, dynamic decisions
    - – need more run-time support

- Whittaker/Thomason:
  - ▷ Basic testing chain from Markov chain
  - ▷ Incorporating failure data
  - ▷ Results and result analysis:
    - – testing vs. usage comparison
    - – mean-steps-between-failures

Markov/UMM: Testcase Generation

- Avritzer/Weyuker (TSE 21, 9/95):
  - ▷ Both coverage &usage,
  - ▷ Off-line test case generation
  - ▷ Path probability and coverage:
    – overall testing, similar to Musa OP.
  - ▷ Node probability and coverage:
    – critical component testing
  - ▷ Call-pair probability and coverage:
    – transition/interface testing

- Hierarchical testing with UMMs
  - ▷ High level coverage
  - ▷ Low level selective/statistical testing
  - ▷ Dynamic expansion

UMM in Web Testing

- Web testing factors:
  - ▷ Existing: coverage-based testing
  - ▷ Web size, complexity, user focus
  - ▷ Dynamic nature
  - ▷ Focus on source failures
  - ▷ Statistical web testing
    – modeling, testing, result analysis

- Measurement and analysis support:
  - ▷ Model construction: access-log
  - ▷ Analysis: error-/access-logs
  - ▷ Some existing analyzers

Statistical Web Testing

- High level testing: UMMs
  - ▷ Overall structure and linkage
  - ▷ Usage and criticality information
  - ▷ Guide/drive low level testing
  - ▷ Performance and reliability analyses

- Low level testing:
  - ▷ HTML checkers
  - ▷ Other existing tools
  - ▷ Future: formal spec. checker

UMMs: Web Usage Modeling

129.119.4.17 - - [16/Aug/1999:00:00:11 -0500] "GET /img/XredSeal.gif HTTP/1.1" 301 328 "http://www.seas.smu.edu/" "Mozilla/4.0 (compatible; MSIE 4.01; Windows NT)"

....

129.119.4.17 - - [16/Aug/1999:00:00:11 -0500] "GET /img/ecom.gif HTTP/1.1" 304 - "http://www.seas.smu.edu/" "Mozilla/4.0 (compatible; MSIE 4.01; Windows NT)".

- Example access log: Fig 10.5 (p.168)

- Web usage modeling based on information extracted from web access logs.

UMMs: Web Usage Modeling

- Access log analysis:
  - ▷ Access frequency from different users
  - ▷ Timing analysis of accesses
  - ▷ Network traffic and performance

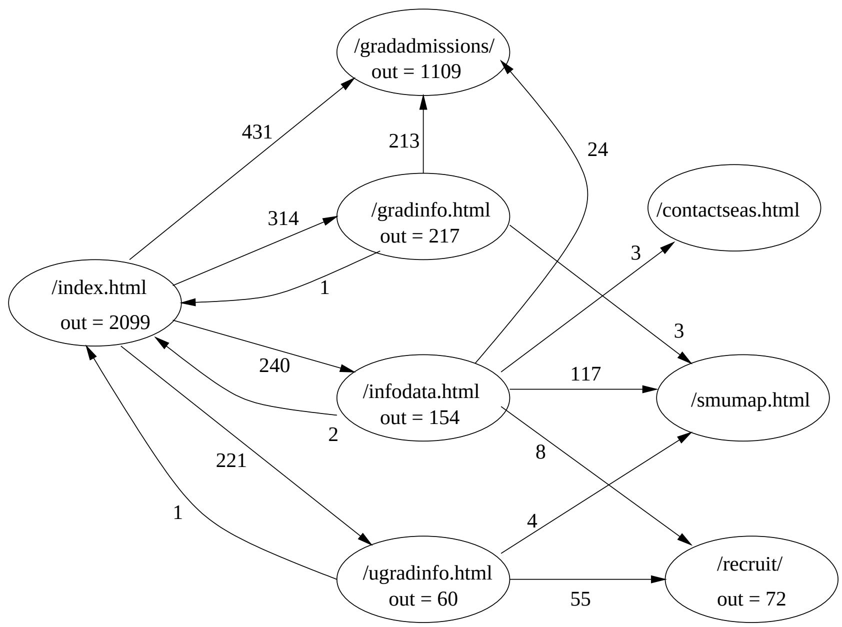
- For usage-based web testing?
  - ▷ usage patterns and frequencies
  - ▷ usage model: UMMs
  - ▷ using existing tool, e.g., FastStats, for summary statistics etc.
  - ▷ new utility programs for other purposes
  - ▷ missing information: need extra effort and ways to collect additional data.

UMMs: Web Usage Modeling

Entry Page	Occurrences
/index.html	18646
/ce/index.html	2778
/co/cams/index.html	2568
/ce/smu/index.html	2327
/netech/index.html	2139
/disted/phd/index.html	1036
/co/cams/clemscam.html	963
/disted/index.html	878
/cse/index.html	813

- Entry pages: Table 10.2 (p.170)
- Skewed distribution $\Rightarrow$ single top model
- Exit pages: implicit.

UMMs: Web Usage Modeling



- Top level model: Fig 10.6 (p.170)
  - ▷ Node and link information: #s not probabilities due to omission.
  - ▷ Selection of top-hit pages.
  - ▷ Grouping of low-hit pages.
  - ▷ Lower level models connected to this.

UMMs vs. Musa

- Flat (Musa) vs. Markovian OPs
  - ▷ Granularity and sequencing differences
  - ▷ Use in test case generation
    - Musa: direct test cases
    - Markov: tool to generate test cases
  - ▷ Use in reliability analysis
    - overall (both) vs. localized (Markov)

- Common issues:
  - ▷ Musa's 5 steps applicable to both
  - ▷ Focus on customer and reliability
  - ▷ Information collection

- Integrating Markov and Musa OPs (and traditional testing): Chapter 12.

Choice: Musa vs Markov/UMM

- External (primary) factors to consider:
  - ▷ Product size
  - ▷ Product/usage structure
  - ▷ Link/sequence of operations
  - ▷ Granularity of info. available

- Internal (secondary) factors to consider:
  - ▷ Ability to handle complexity
  - ▷ Desired level of detail
  - ▷ Tool support

- Key: What does the user see?
  (unit of operation or in a lump?)

Conversion: Musa $\Leftrightarrow$ Markov

- Is conversion meaningful?

- Musa to Markovian:
  - ▷ enough info?
  - ▷ additional information gathering
  - ▷ additional analysis/construction

- Markovian to Musa:
  - ▷ prob(path) from prob(links)
  - ▷ loops $\Rightarrow$ prob. threshold
  - ▷ mostly related to test case generation

Summary and Comparison

- FSMs and Markov-OPs/UMMs:
  - ▷ More complex operations/interactions
  - ▷ More complex models too!
  - ▷ Need algorithm and tool support for analysis and testing.
  - ▷ Difficulties with FSMs: state explosion $\Rightarrow$ UBST with Markov-OPs/UMMs

- FSM testing focus on traversal of individual states and links $\Rightarrow$ extend FSMs to test problems involving more states/links:
  - ▷ specialized FSM to test execution paths
  - ▷ test related data dependencies?
  - ▷ CFT and DFT techniques (Ch.11)