Statistical testing of software

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Background

- Question: How do we measure the quality of our software?
- Started reading about the two software development processes:
  - *Cleanroom Software Engineering* (Mills et al) and;
  - *Software Reliability Engineering* (Musa et al)
- Today I'd like to share my interpretation of what those two camps have to say about the above question, and show how one might go about implementing (the testing part) of their ideas

Overview

- What are *Cleanroom Software Engineering* and *Software Reliability Engineering*?
  - History, in what context where they developed
  - Main points of the two methods, focusing on the (statistical) testing part
- How can we implement their testing ideas using property-based testing

Harlan Mills (1919-1996)

- PhD in Mathematics, 1952
- Worked at IBM from 1964 to 1987
- Founded *Software Engineering Technology, Inc* in 1987 (later acquired by Q-Labs)
- Visiting professor (part-time), 1975-1987
- Adjunct professor, 1987-1995
- Published 6 books and some 50 articles

What is *Cleanroom Software Engineering*?

- A complete software development process developed by Mills and many others at IBM
- Goal: Bug prevention, rather than removal (achieve or approach zero bugs)
- Controversial
  - Developers and testers are separate teams
  - Relies on formal methods/specifications, stepwise refinement, and design/code verification/review at each step to prevent bugs
  - Developers have no access to compilers, and are not supposed to write tests
  - Testers job isn't to find bugs, but to measure the quality (end-to-end black box tests only)
  - Claims to be academic, criticised by Dijkstra
- Many case studies with positive outcomes

John Musa (1933-2009)

- Went to Naval ROTC, became an electrical officer
- Started working at AT&T Bell Labs in 1958
- Started working on SRE in 1973, while managing the work on an anti-ballistic missile system
- Published first paper *A Theory of Software Reliability and Its Application* (Musa 1975)
- Published 3 books and some 100 papers

What is *Software Reliability Engineering*?

- Also a development process, but not as complete as Cleanroom, developed by Musa and others at AT&T Bell Labs
- Goal: Estimate the time/cost to deliver software of some given quality/reliability
- Testing part overlaps greatly with that of Cleanroom Software Engineering
- SRE became best current practice at AT&T in 1991
- Adopted by many others after positive case studies

Statistical testing and reliability certification

- Statistics in general: used when a population is too large to study, a statistically correct sample must be drawn as a basis for inference about the population
- Idea: Test the products of software engineers in the same way we test the products of other engineers
- Take a random sample of the product, test if it's correct with regards to the specification under operational use, make analytical and statistical inferences about the reliability, products meeting a standard are certified as fit for use

Statistical testing as a statistical experiment

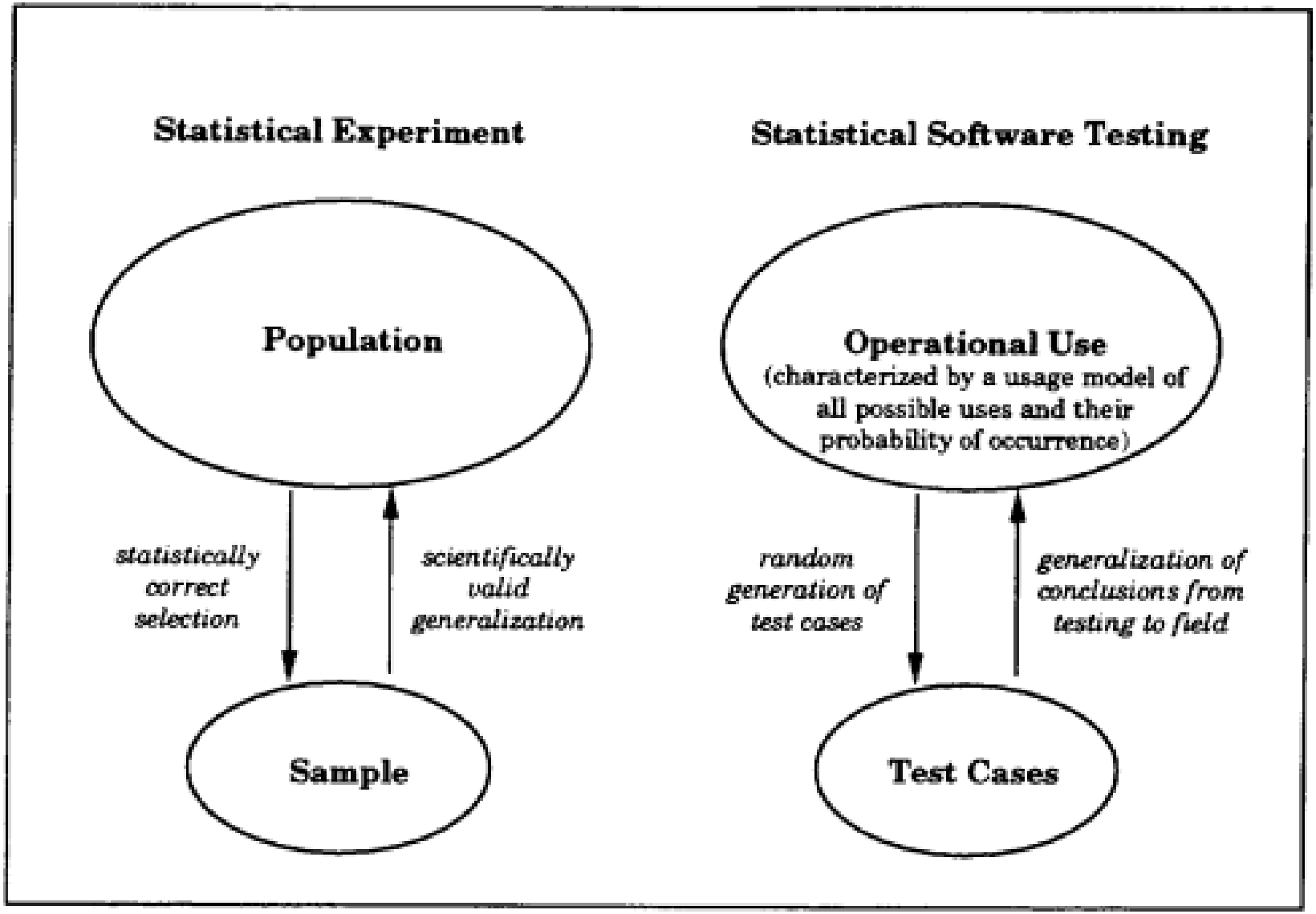


Figure 1: Picture by Trammell (1995)

Modelling operational use

- Operational use is captured by a usage model (Cleanroom) or an operational profile (SRE)
- We can define a usage model by asking the questions:
  1. Who are the customers and what are their users and their goals?
  2. What are the use cases?
  3. How often do the use cases happen in relation to each other?
- There are different ways to encode this information, e.g. formal grammars (property-based testing) or Markov chains

Usage model example, process registry

- What are the users? The developer that uses the process registry API:

```
spawn      :: IO Pid
register   :: Pid -> Name -> IO ()
whereis    :: Name -> IO Pid
unregister :: Name -> IO ()
kill       :: Pid -> IO ()
```

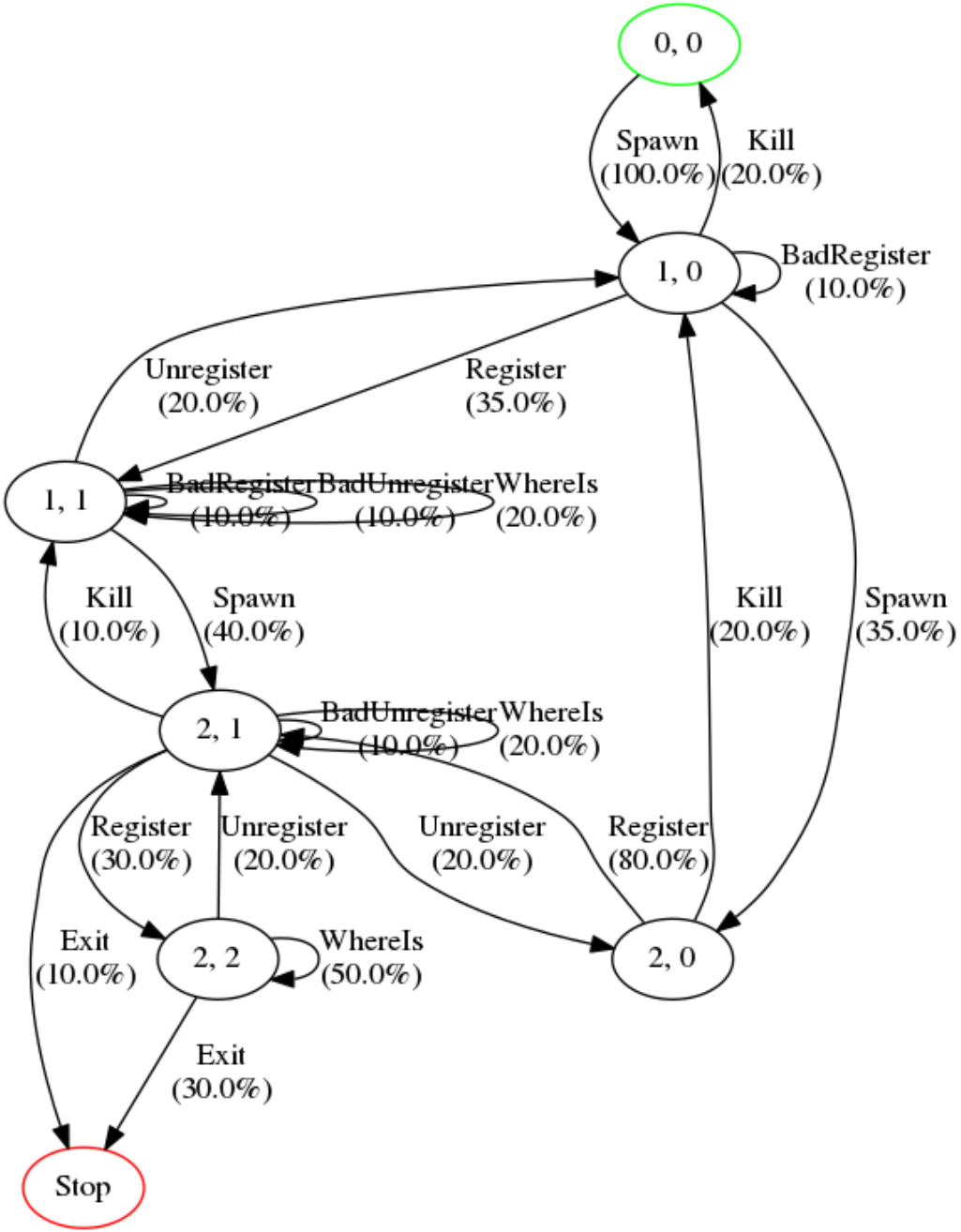
- What are the use cases? Calls to the API!
- How often do the use cases happen in relation to each other?
  - Spawning, registering, looking up names is the most likely happy path
  - The above with some unregisters and kills interleaved that happen with less frequently than the lookups seems realistic
  - If we want to be precise, we could e.g. study production logs

Formal grammar usage model for process registry

```
data Action = Spawn | Register Pid Name | Kill ...

gen :: (Int, Int) -> Gen [Action]
gen (spawned, registered) = case (spawned, registered) of
  (0, 0) -> liftM (Spawn :) (gen (1, 0))
  (1, 0) -> frequency
    [ (35, liftM (Register (Pid 0) (Name "0") :)
                 (gen (1, 1)))
    , (20, liftM (Kill (Pid 0) :) (gen (0, 0)))
    , ...
    ]
  ...
```

Markov chain usage model for process registry



Other uses of the Markov chain usage model

- Markov chains have been very well studied in statistics and other fields
- Examples of analytic computations we can do without running any tests:
  - Calculate the expected test case length
  - Number of test cases required to cover all states/arcs in the usage model
  - Expected proportion of time spent in each state/arc
  - Expected number of test cases to first occurrence of each state/arc
  - For more see S. J. Prowell (2000) and the JUMBL tool
- The usage model can also guide development work (Pareto principle: 20% of use cases support 80% of the system use)

Statistical testing as a statistical experiment

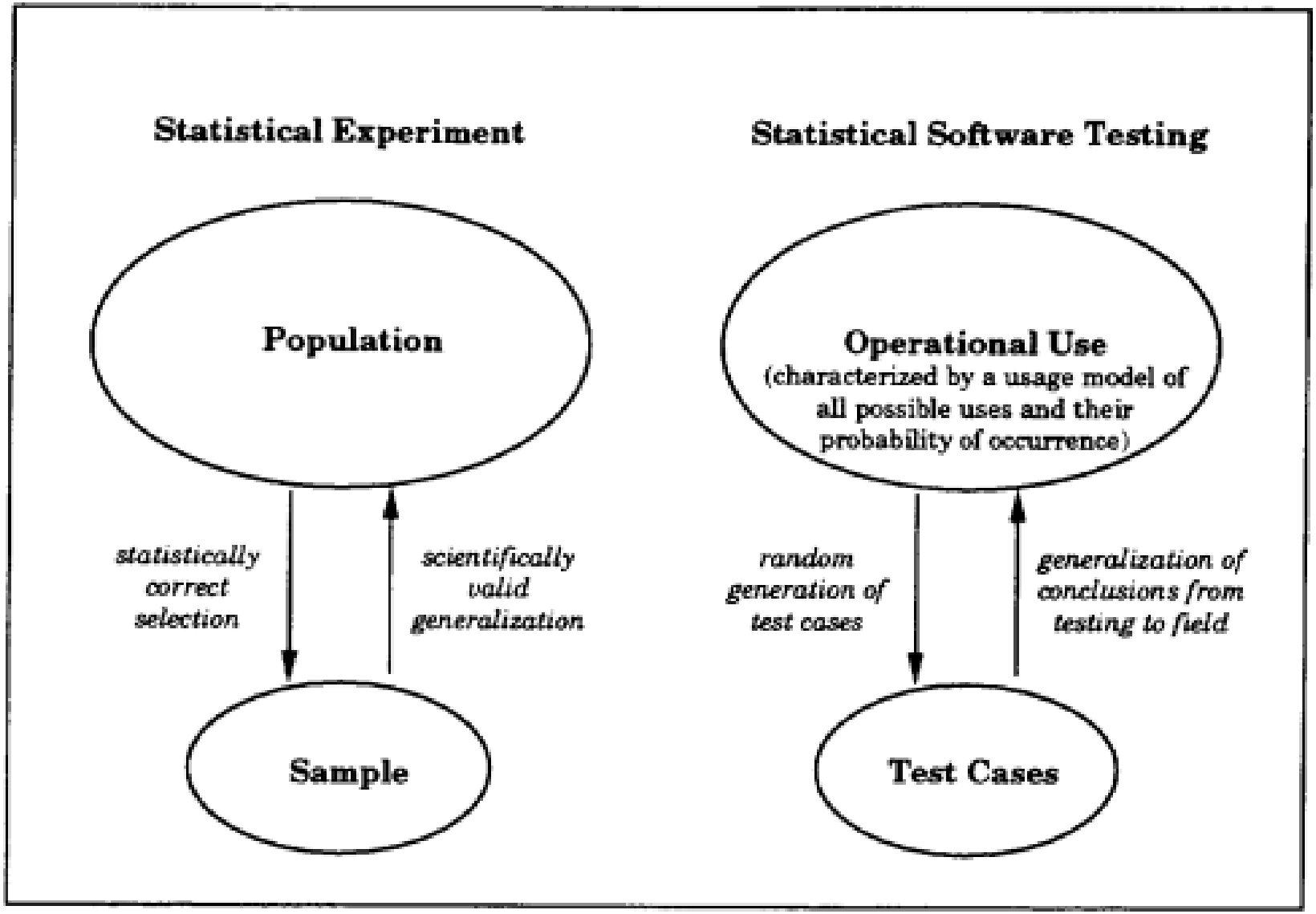


Figure 2: Picture by Trammell (1995)

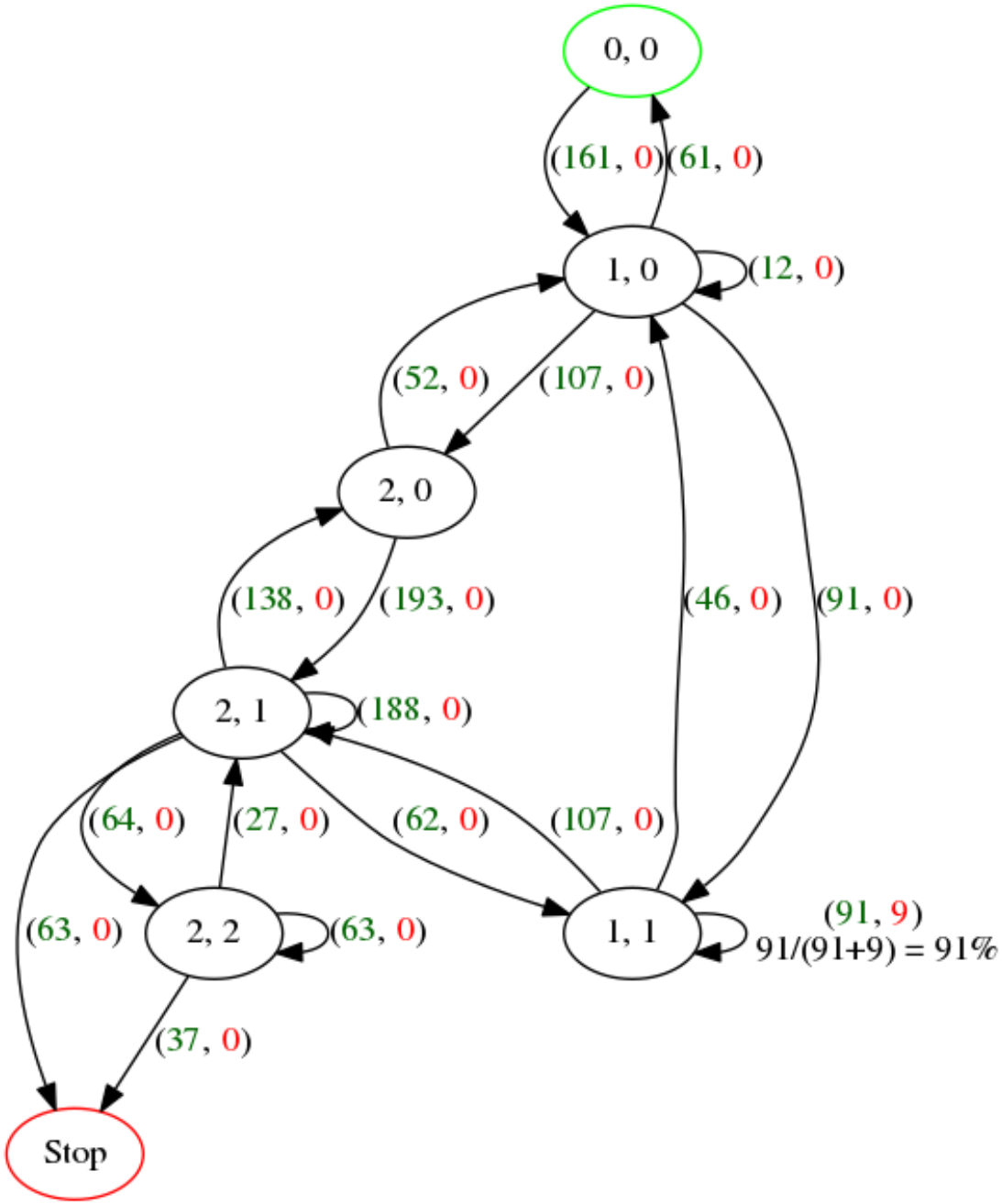
Bernoulli sampling model for computing reliability

- Reliability = 1 - 1 / MTTF (mean time to failure, where time could be number of test cases) (See: Poore, Mills, and Mutchler 1993)
- Number of test cases = log(1 - Confidence) / log(Reliability)
- E.g. To achieve 0.999 reliability with 95% confidence we need 2995 test cases to pass without failure
- Idea: pick desired confidence and reliability, calculate number of test cases needed, use QuickCheck to generate said many test cases
- Shortcomings
  - Coarse-grained, did the whole test case succeed or not
  - Doesn't take test case length into account
  - Doesn't allow the presence of failures (consider flaky tests)

Arc-based Bayesian model for computing reliability

- More fine-grained, count successful and unsuccessful state transitions (arcs)
- Compute the overall reliability (and variance) from the above, and taking the Markov chain probabilities and the probability mass for each sequence/test case
- More complicated, see Stacy J. Prowell and Poore (2004), and Xue et al. (2018) for details
- There are other ways to compute the reliability, but this seems to be the latest one published in the literature that I could find. It's also used by the JUMBL tool

A testing Markov chain constructed from test experience



Demo: Computing reliability for process registry example

Statistical testing inspired changes to standard property-based testing

- Generate programs using a Markov chain usage model
- Persist test results (about state transition reliability)
- Don't stop in presence of failures
- Compute reliability (and variance) from the usage model and test experience

Conclusion and further work

- Compare to other ways of measuring quality? Cleanroom people claim:
  - Bugs/kloc: too developer centric
  - Code coverage: less cost effective
- Both statistical testing and property-based testing use a random sample, is there more we can learn from statistical testing than computing the reliability?
  - Can we add combinators to our property-based testing libraries to make it easier to do statistical testing?
  - Can we in a statistically sound way account for flakiness in tests this way?
  - How do we account for incremental development? When testing version $n + 1$ of some software, we should be able reuse some of the test experience from version n

Questions?

Extra slide: Notes from researching Mills and Musa

- Mills' bibliography
- Musa's bibliography
- Q-Labs' collaboration with Software Engeinnering Technology is documented here, it doesn't say anything about the acquisition though.
- Q-Labs later became Addalot Consulting AB
- More about Mills
- Interview with Musa
- Dijkstra's (harsh) comments on Mills' work

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