Turret: A Platform for Automated Adversarial Testing of Distributed Systems and Network Protocols

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Dependable and Secure Distributed Systems

Research Overview

- Overarching goal:
  - Create and build distributed systems and network protocols that achieve **security**, **availability**, and **performance** in spite of *failures*, *misconfigurations*, and *attacks*
- Approach:
  - Combine theoretical principles and experimental methodologies from distributed systems, cryptography, networking, information theory, and machine learning
  - Create systems and protocols based on provable guarantees and validated in realistic environments

Challenges for Building Trustworthy Systems

- **Failures**:
  - Computers and networks fail in many (often unpredictable) ways
- **Attacks**:
  - Computers get compromised
- **Constraints:**
  - Real-time constraints
- **Requirements**:
  - Performance requirements
- **Complexity**:
  - Complex systems fail in complex ways

Towards Robust Systems and Protocols

- Model checking
  - Mathematically check if the design meets its goals at every possible state
- Simulation
  - Test correctness and performance under various environments
- Real deployments
  - Capture traces, use replaying for debugging

But …

- Model checking
  - Design choices made at implementation time are not captured by models
  - New vulnerabilities introduced during implementation
- Simulation
  - Does not capture the interaction between protocols and OS
- Real deployments
  - Difficult and expensive
  - Better to find problems before they occur in the wild

Adversarial Testing of Implementations

- Test software beyond its functionality by
  - Examining edge cases
  - Testing boundary conditions
  - Conducting destructive testing (insider attacks)
- Captures both bugs and vulnerabilities
- Allows testing for insider attacks
- Realistic environments: binaries in native environment with reproducible conditions

Testing for Performance Degradation

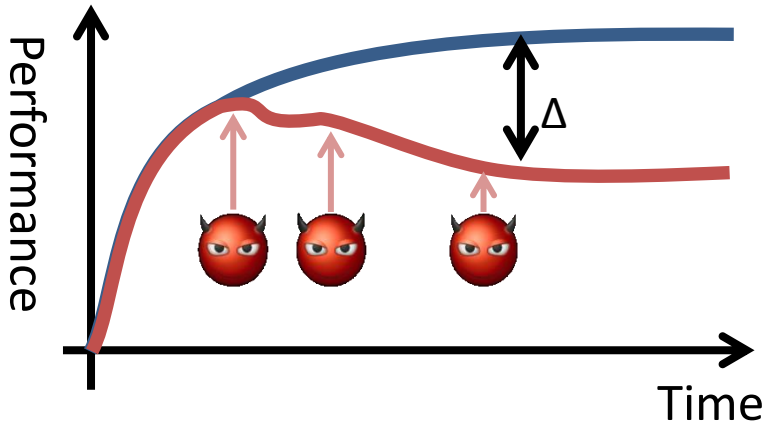
- A correct but slow system might not be that useful
- Slow processing might be an indication of a bigger issue
- Slow performance might mean money both for service provider and users
  - Some sources estimate that Amazon gets $9,823 every five seconds.

Our Focus

Automated adversarial testing for implementations of distributed systems and protocols in realistic environments, looking at significant degradation of performance

Performance Attacks

- **Performance attacks**: attacks that make the system slow down
  - While the network is stable, the distributed system or network protocol does not achieve the performance that it can achieve
- A set of actions that:
  - deviate from the protocol
  - taken by a group of malicious nodes
  - Δ-worse than benign scenario in performance

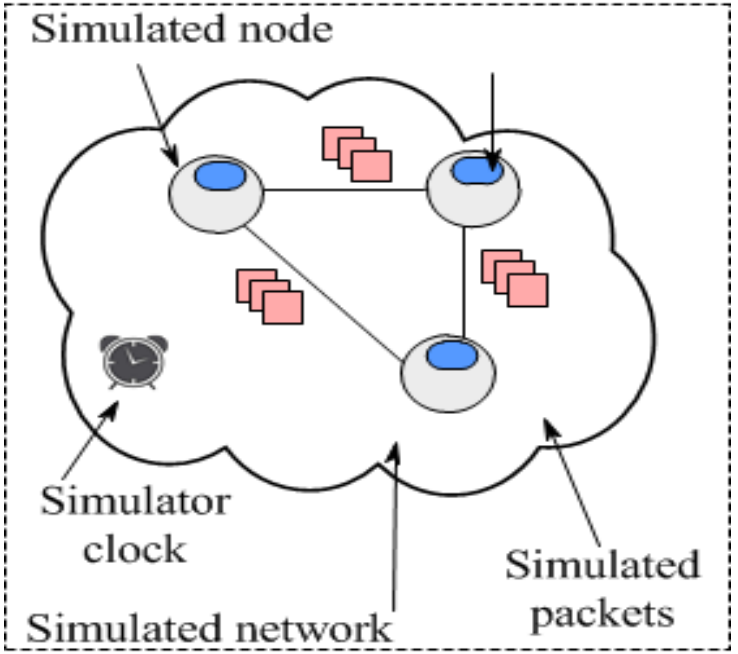


Malicious Actions through Messages

- Message delivery actions
  - Delay
  - Divert
  - Duplicate
  - Drop
- Message manipulation actions: lie field by field (based on field type range and on original value)
  - Min and max
  - Zero
  - Scaling
  - Spanning
  - Random

Our Previous Work: Gatling

- Fault injector: Basic message delivery and manipulation actions
- Model checker: Greedy algorithm builds up attack
- Framework: Event-based simulator combining model checking and fault injection in the Mace toolkit
- Found 48 attacks in 9 systems



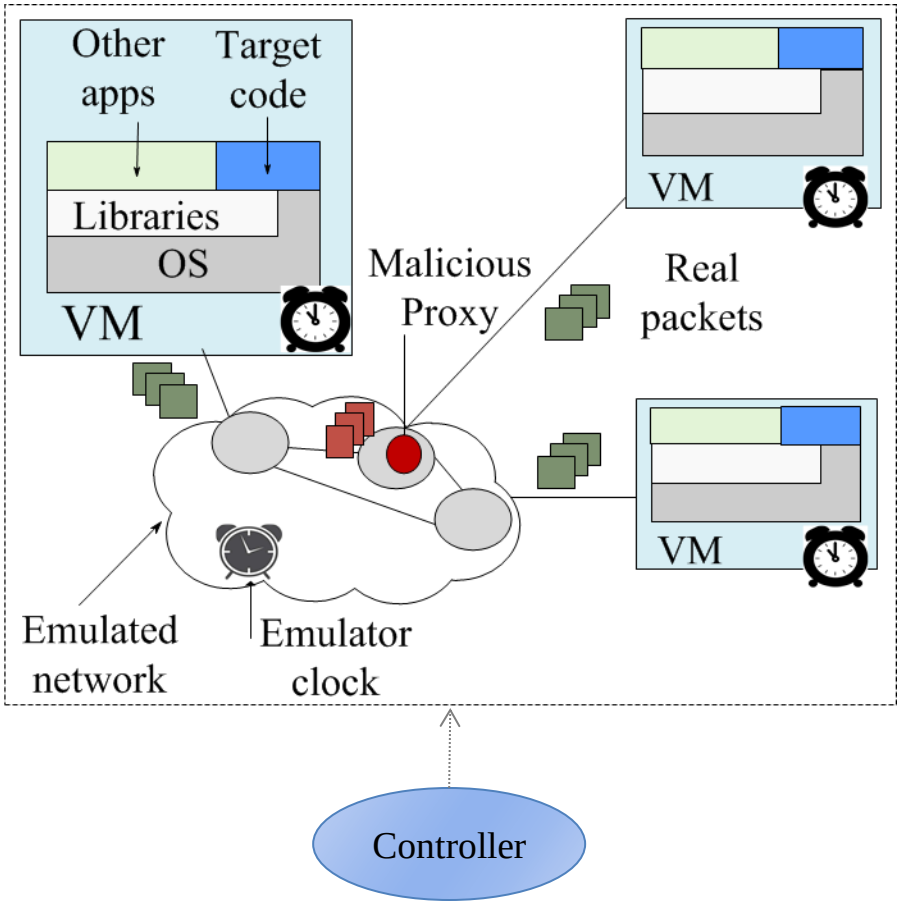
Gatling: Automatic Attack Discovery in Large-Scale Distributed Systems.
J. Seibert, HJ. Lee, C. Killian, and C. Nita-Rotaru. Proc. of NDSS 2012.

Gatling Limitations

- Systems need to be rewritten in MACE if they were written in other languages
- Source-to-source compiler to get the deployed binary
- The testing environment does not capture the deployment environment: Vulnerabilities are often related to the environment: OS, libraries, etc

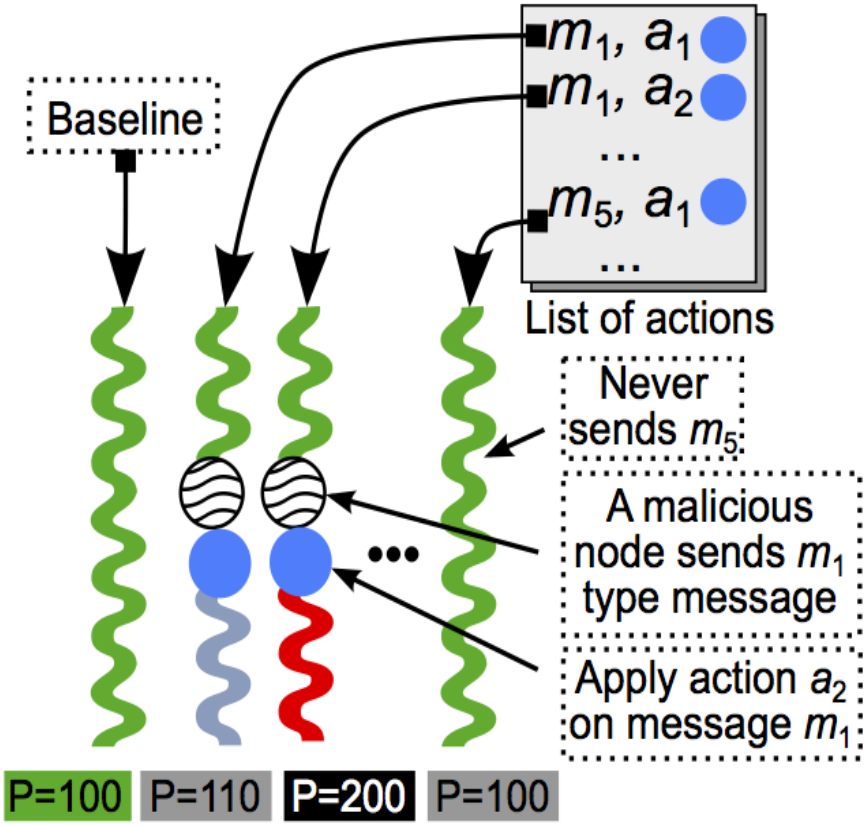
Turret Design Overview

- Test unmodified implementation
- Environment as close to the deployment environment as possible
  - OS, libraries, etc.
- Inject malicious actions
- Reproducible results



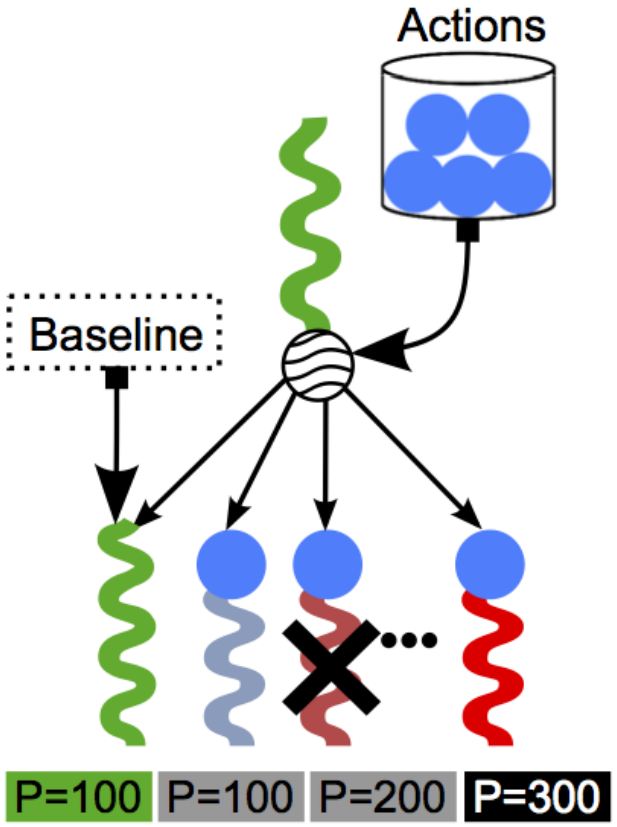
Attack Finding Algorithms: Brute Force

- Approach
  - Pre-generate strategies
  - Run each strategy and evaluate performance
- Pros.
  - Simple: Does not require control during the execution of an attack scenario, but just the ability to start the system and stop it
- Cons.
  - Overhead: Wastes time due to unnecessary executions (system runs in real time)



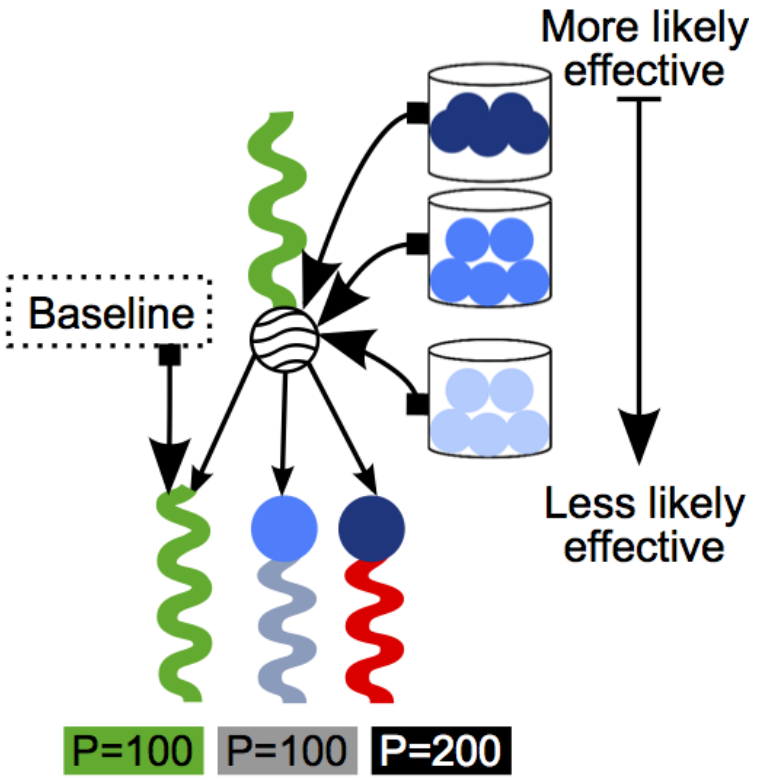
Attack Finding Algorithms: Greedy

- Approach
  - Test all actions for a message type and select greedily (strongest) at each branch point
  - Repeat until confident
- Pros.
  - Can build up attacks
  - Saves some unnecessary executions
- Cons.
  - Some redundant executions
  - More complex as it requires execution branching



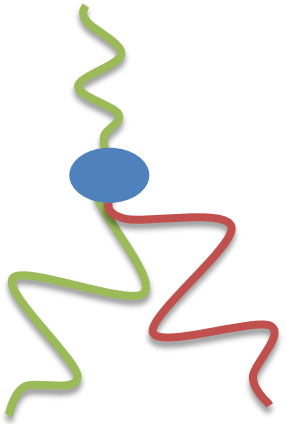
Attack Finding Algorithms: Weighted Greedy

- Approach
  - Prioritize actions based on history
- Pros.
  - More efficient: Removes redundant execution
- Cons.
  - Still requires execution branching

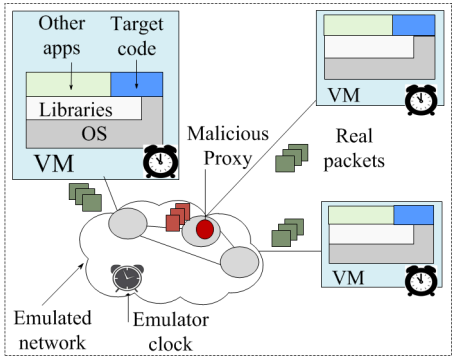


Design: Execution Branching

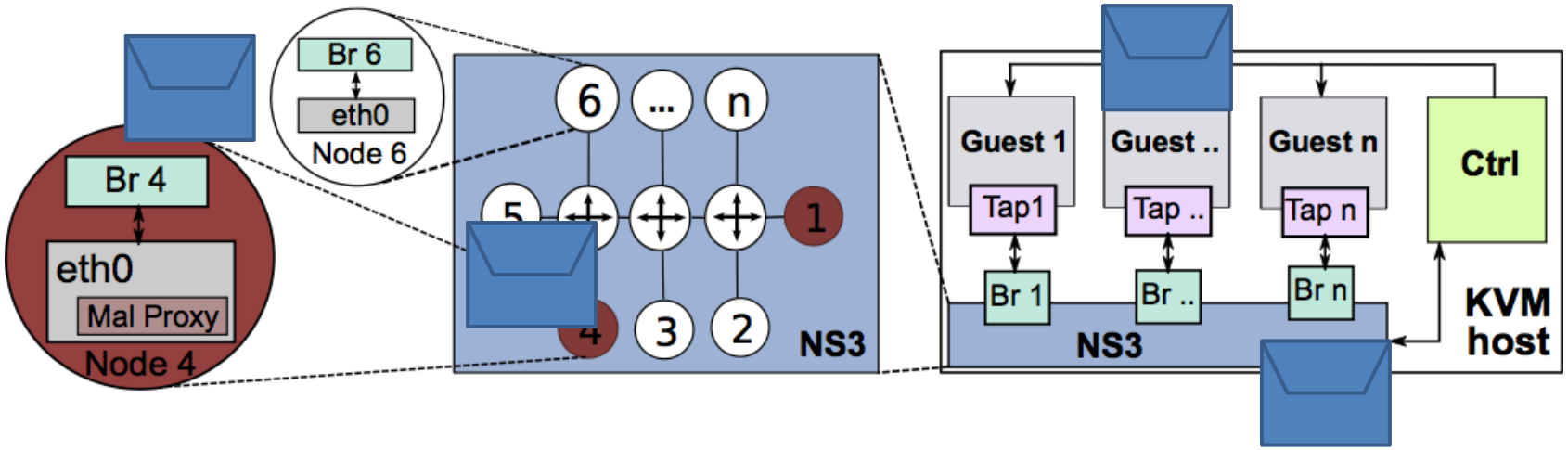
- Checkpointing methods
  - Log/replay execution
  - **Take/load snapshot**



- Taking snapshot of the entire distributed system
  - State of nodes + messages on the fly



Implementation



Turret: A Platform for Automated Attack Finding in Unmodified Implementations of Distributed Systems H. Lee, J. Seibert, C. Killian, and C. Nita-Rotaru. ICDCS 2014.

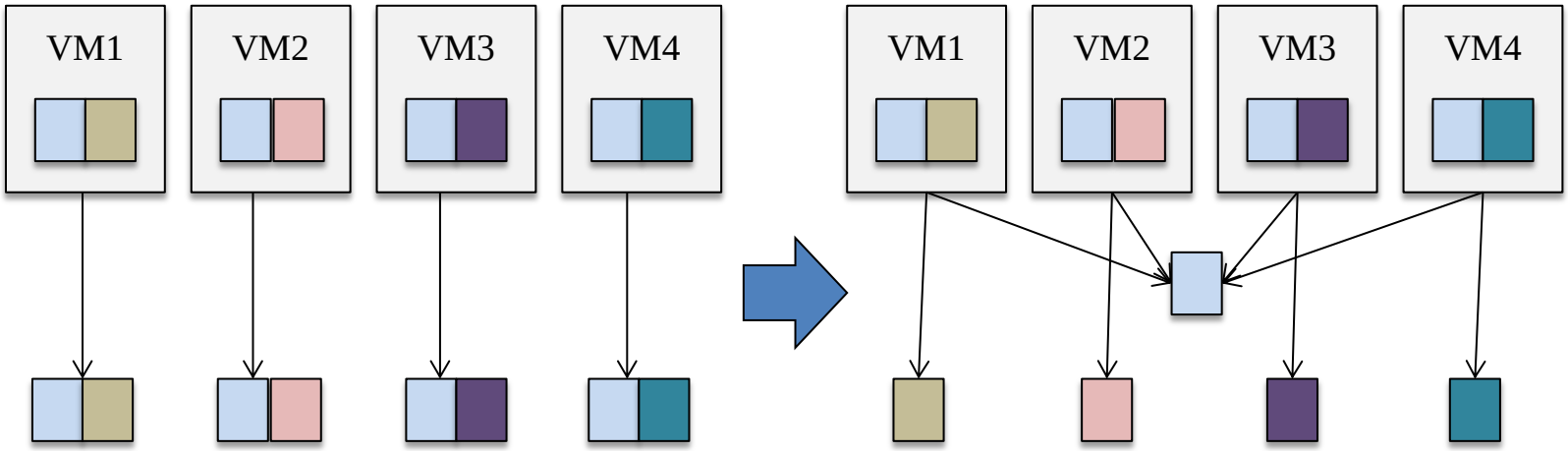
Implementation: Malicious Proxy

- Intercept a packet at the tap device
  - TCP: Send up to application layer to maintain socket status
  - UDP: Strip off headers and modify directly
- Message type based attacks
  - Small compiler to parse message and recognize the type
- Message format provided by user

Implementation: Execution Branching

- NS-3 modification
  - Save / Load
  - Event queue, objects and events
  - Freeze / Resume
  - Separate clock
- KVM modification
  - TSC – used to calibrate drift between host and guest
  - Para-virtual clock: report manipulated TSC

Implementation: Page Sharing Aware Snapshot Management



- KSM: modify to expose sharing information
- KVM: modify to use sharing information

Running Turret

User must

1. Implement a simulation driver
2. Provide an impact score
3. Provide the layout of messages
4. Set several parameters
5. Find attacks!

The user does not need to provide a malicious implementation.

How We Use Turret

- As our ``Red Team'' for testing protocols we create and implement – we use it our protocols developed in the MRC Darpa Grant
- To test distributed systems: tested 5 systems (PBFT, Zyzyva, Aardvak, Steward, Prime), found 30 total, 24 not previously reported problems
- To test wireless routing protocols (the benefit of emulation): tested 5 different protocols (AODV, ARAN, OLSR, DSDV, BATMAN), found 37 attacks and 3 bugs
- As a projects and testing platform in the Distributed Systems class Spring 2013, plan to do it again in Fall 2014

Ongoing Work

- Research:
  - Take into account information about the protocol state machine
  - Scaling to larger systems
- For use in class
  - Integrate better debugging and feedback tools
  - Developing more projects
  - Provide it as a service
- Code and projects will be released in the next few weeks

Conclusion

- Introduced Turret, which automatically finds performance attacks on distributed systems implementations
  - Implemented using KVM and NS3
- Applied Turret to intrusion tolerant systems and wireless routing
- Used it as teaching tool