Self-defending software:

Automatically patching errors in deployed software

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Joint work with:

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Problem: Your code has bugs and vulnerabilities

- Attack detectors exist
  - Code injection, memory errors (buffer overrun)
- Reaction:
  - Crash the application
    - Loss of data
    - Overhead of restart
    - Attack recurs
    - Denial of service
  - Automatically patch the application

ClearView:
Security for legacy software

Requirements:

1. Protect against unknown vulnerabilities
2. Preserve functionality
3. Commercial & legacy software

1. Unknown vulnerabilities

- Proactively prevent attacks via unknown vulnerabilities
  - “Zero-day exploits”
  - No pre-generated signatures
  - No hard-coded fixes
  - No time for human reaction
  - Works for bugs as well as attacks

2. Preserve functionality

- Maintain continuity: application continues to operate despite attacks
- For applications that require high availability
  - Important for mission-critical applications
  - Web servers, air traffic control, communications
- Technique: create a patch (repair the application)
  - Patching is a valuable option for your toolbox

3. Commercial/legacy software

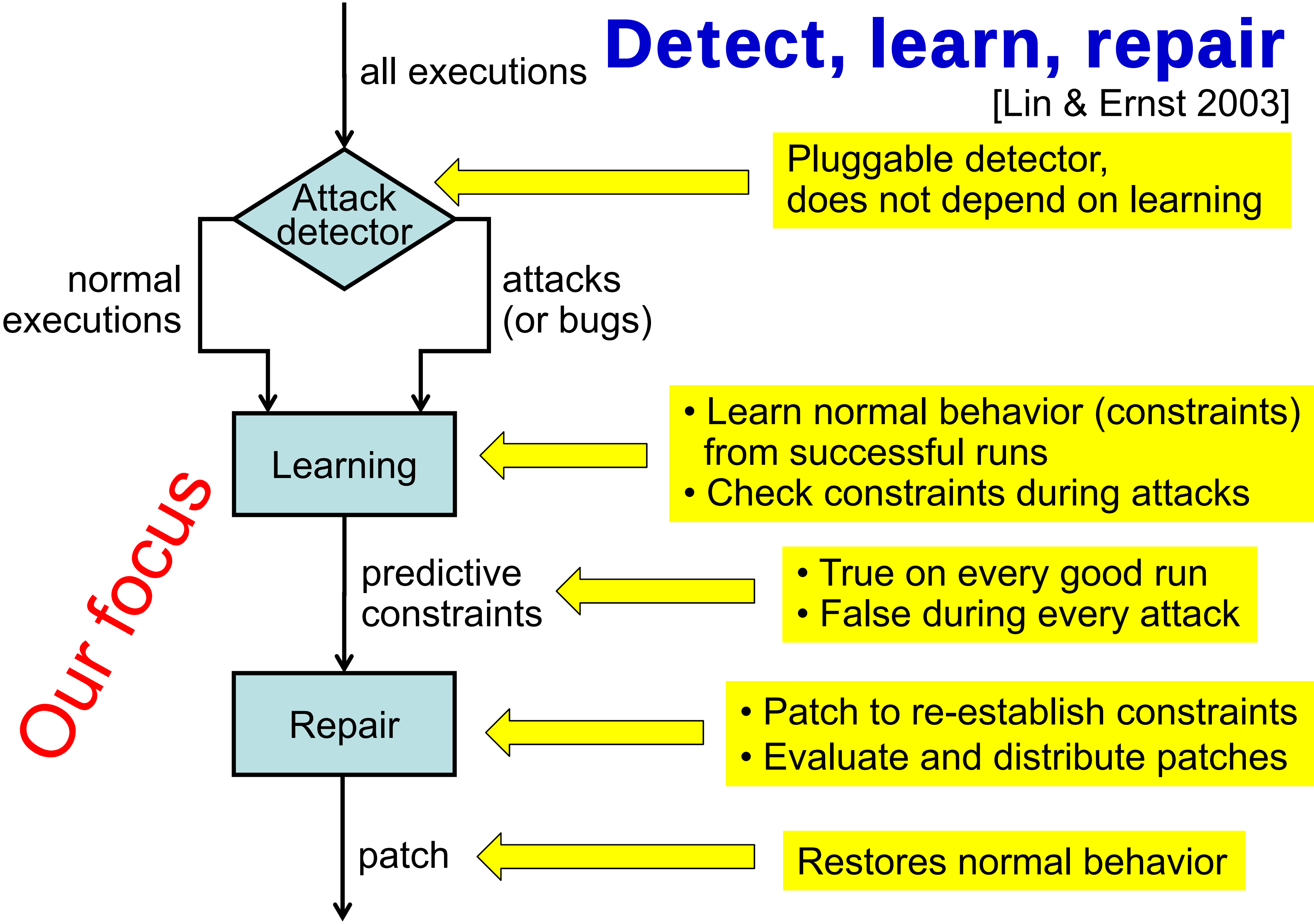
- No modification to source or executables
- No cooperation required from developers
  - Cannot assume built-in survivability features
  - No source information (no debug symbols)
- x86 Windows binaries

Learn from success and failure

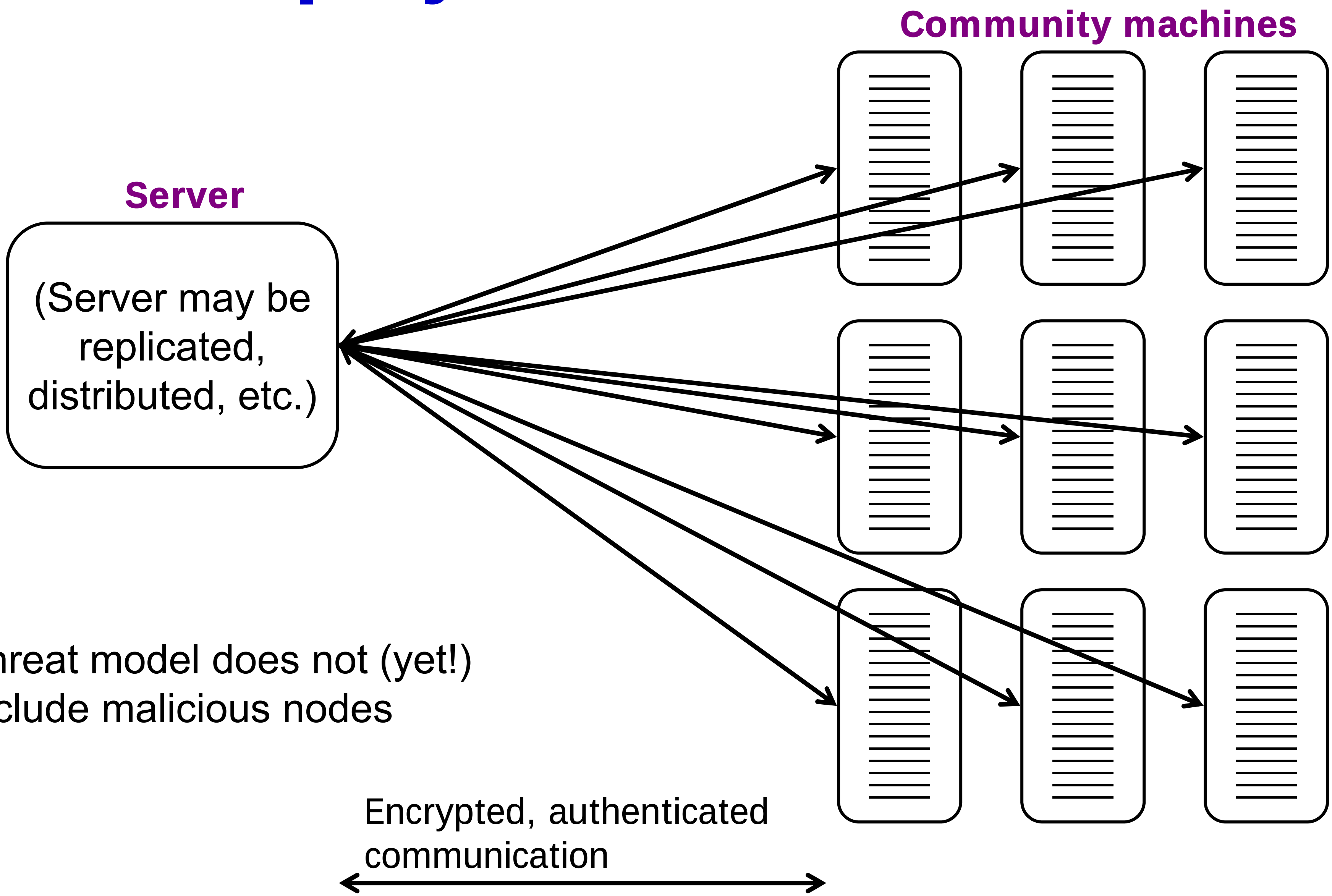
- Normal executions show what the application is supposed to do
- Each attack (or failure) provides information about the underlying vulnerability
- Repairs improve over time
  - Eventually, the attack is rendered harmless
  - Similar to an immune system
- Detect all attacks (of given types)
  - Prevent negative consequences
  - First few attacks may crash the application

Detect, learn, repair

[Lin & Ernst 2003]



A deployment of ClearView

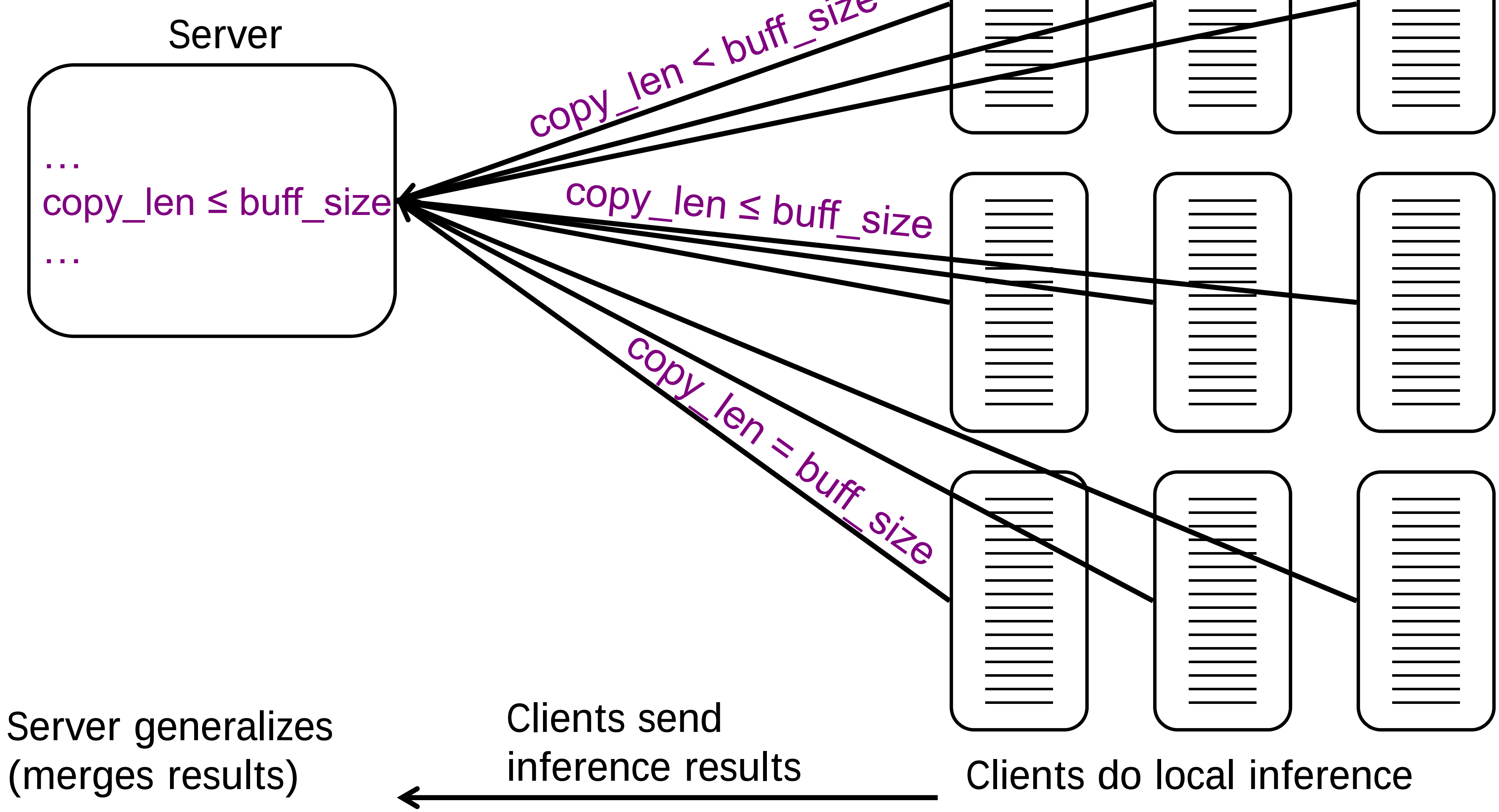


Threat model does not (yet!) include malicious nodes

Learning normal behavior

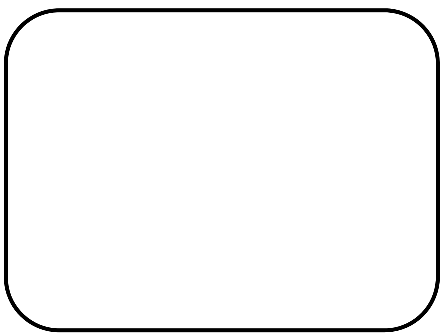
Observe normal behavior

Generalize observed behavior

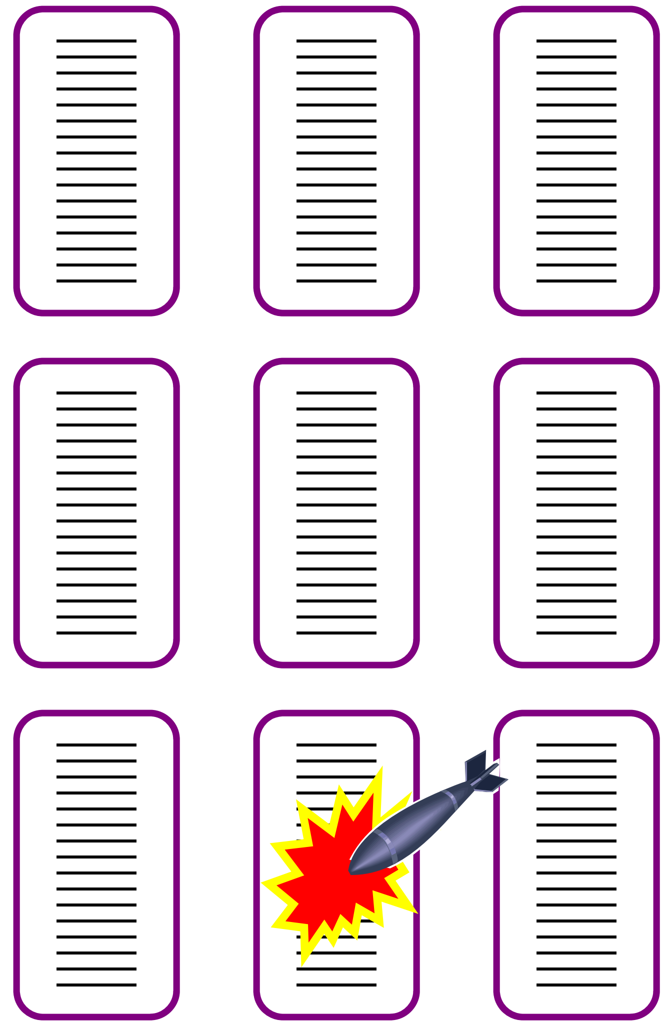


Attack detection & suppression

Server



Community machines



Detector collects information and terminates application

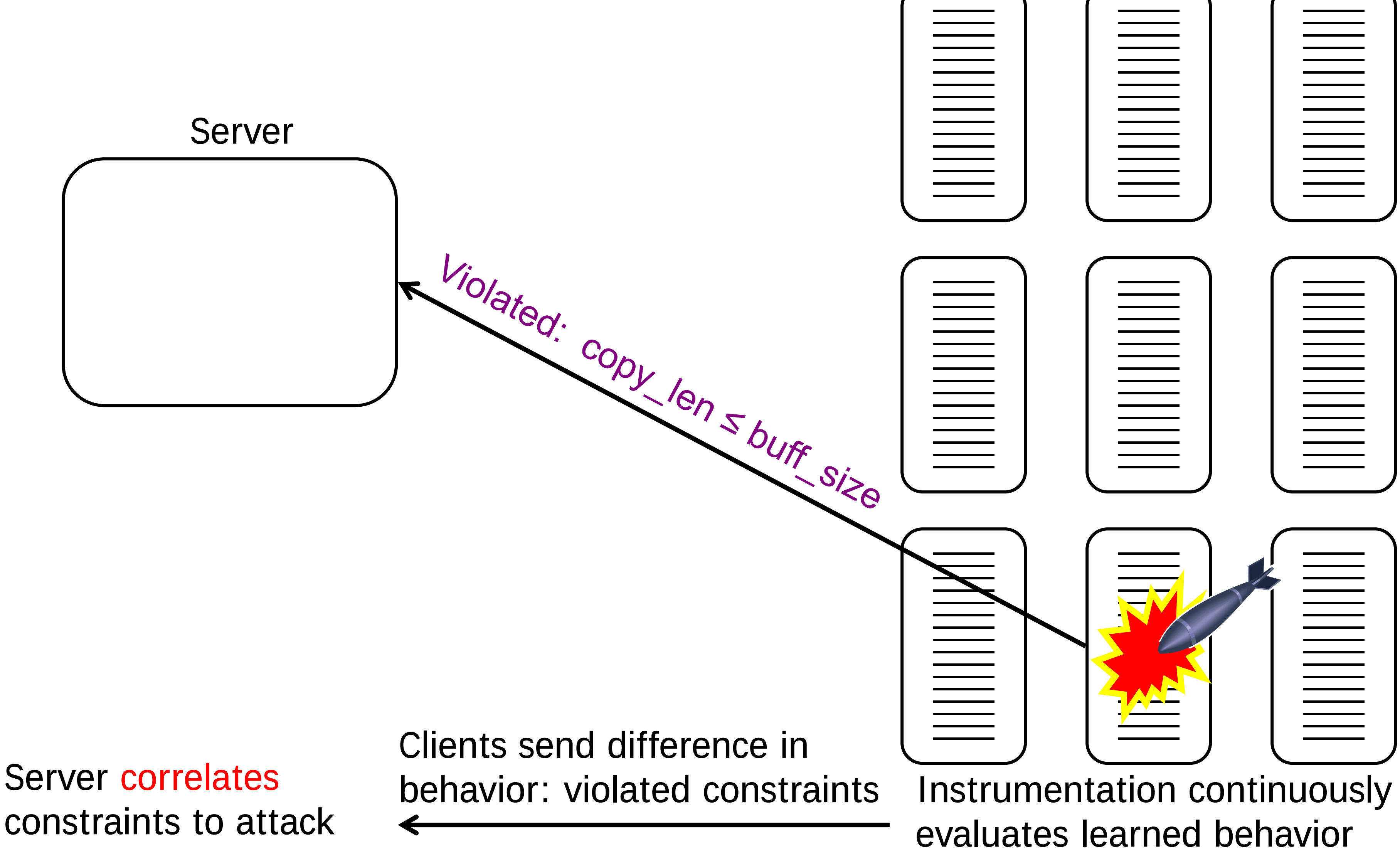
Detectors used in our research:

- Code injection (Memory Firewall)
- Memory corruption (Heap Guard)

Many other possibilities exist

Learning attack behavior

What was the effect of the attack?



Repair

Propose a set of patches for each behavior that predicts the attack

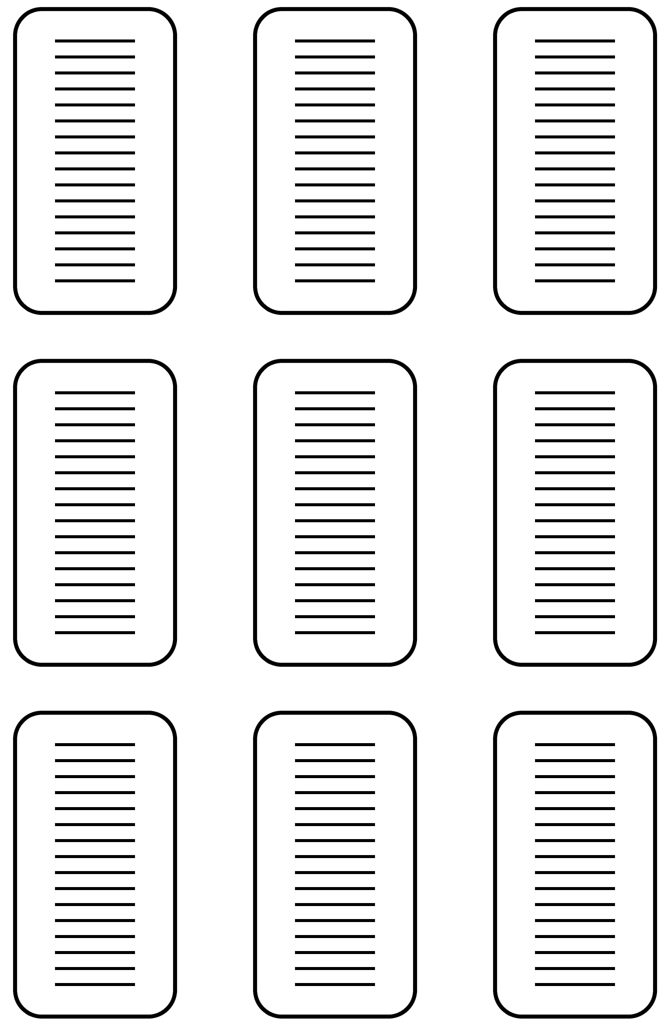
Server

Predictive: copy_len ≤ buff_size

Candidate patches:

1. Set copy_len = buff_size
2. Set copy_len = 0
3. Set buff_size = copy_len
4. Return from procedure

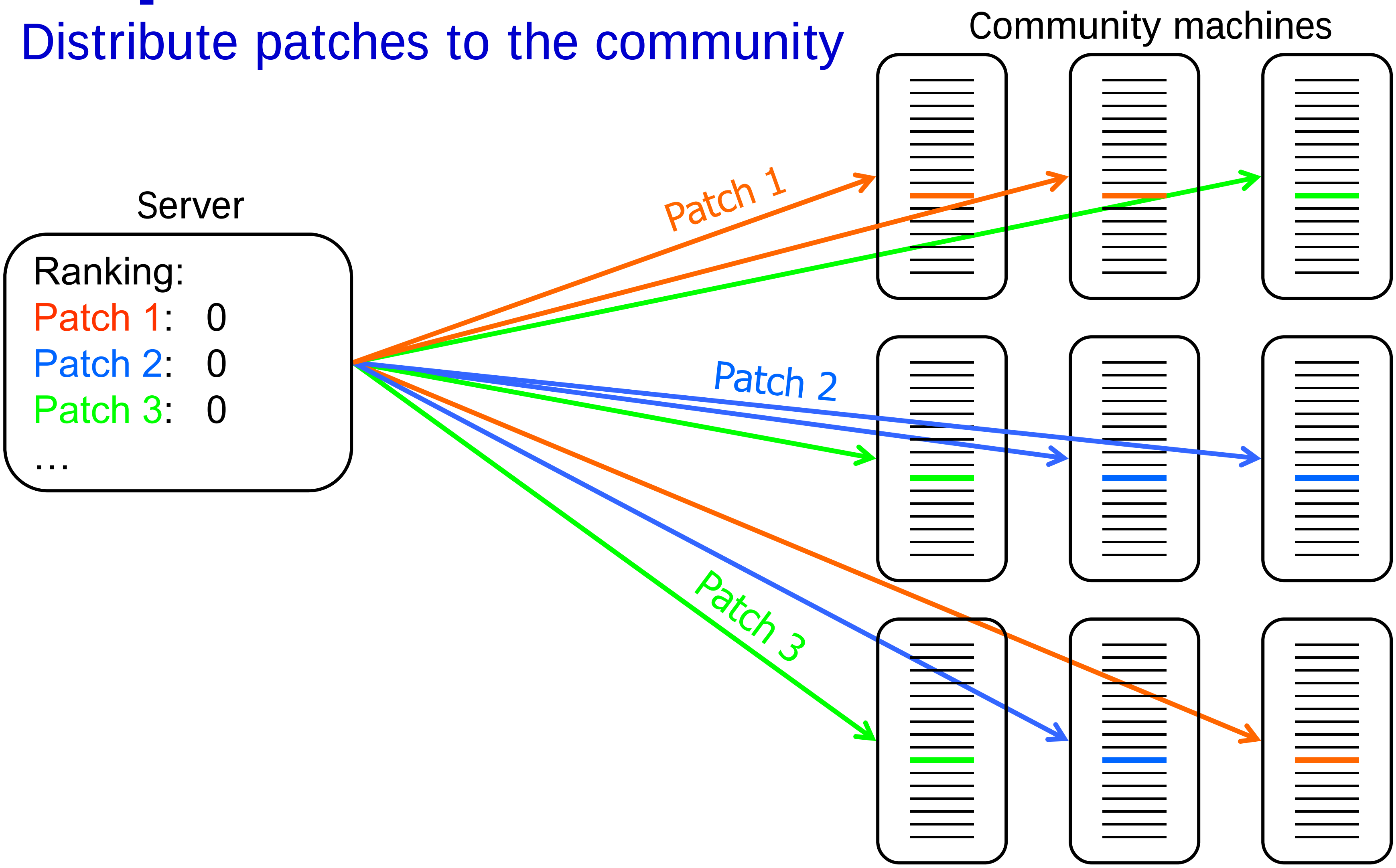
Community machines



Server generates a set of patches

Repair

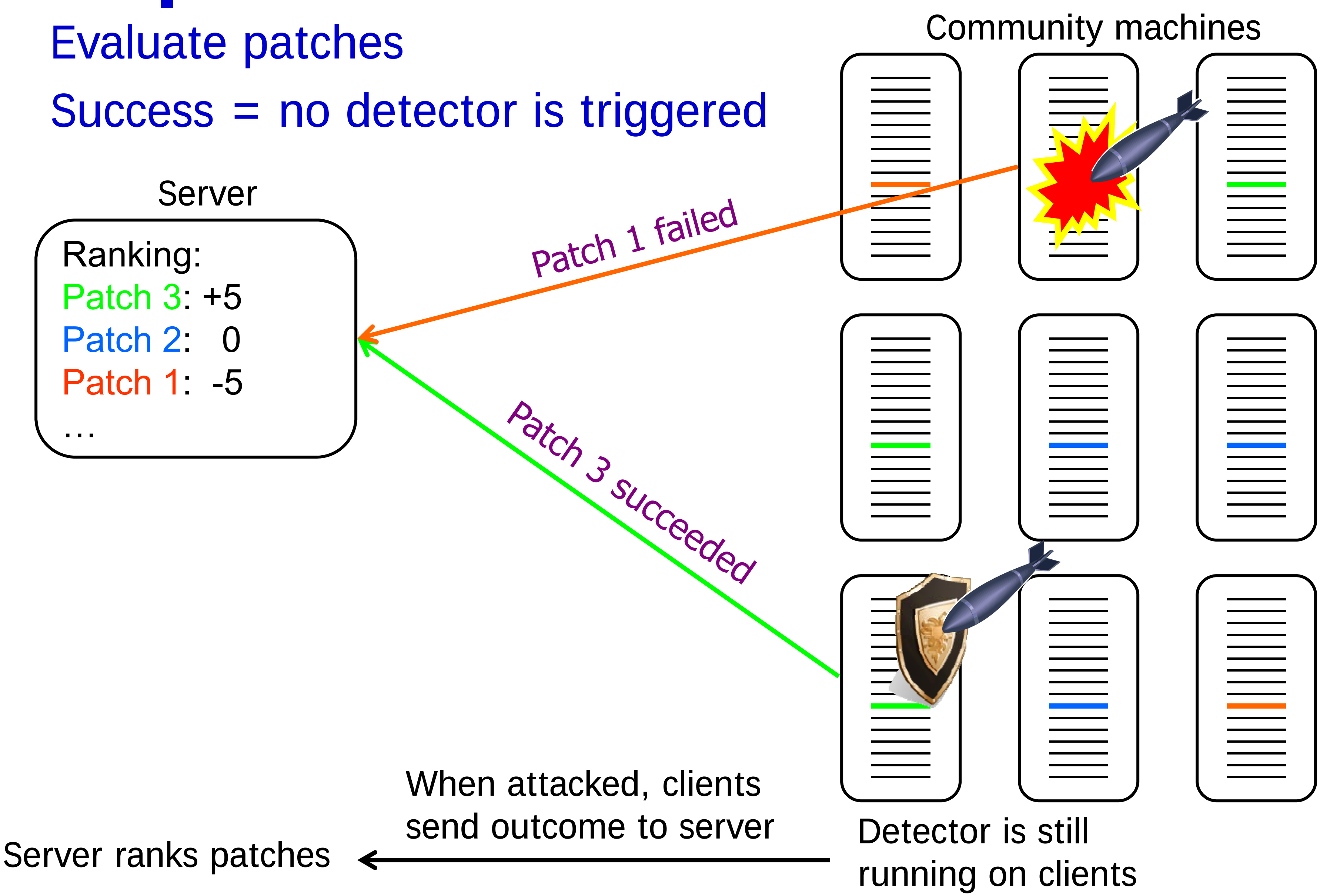
Distribute patches to the community



Repair

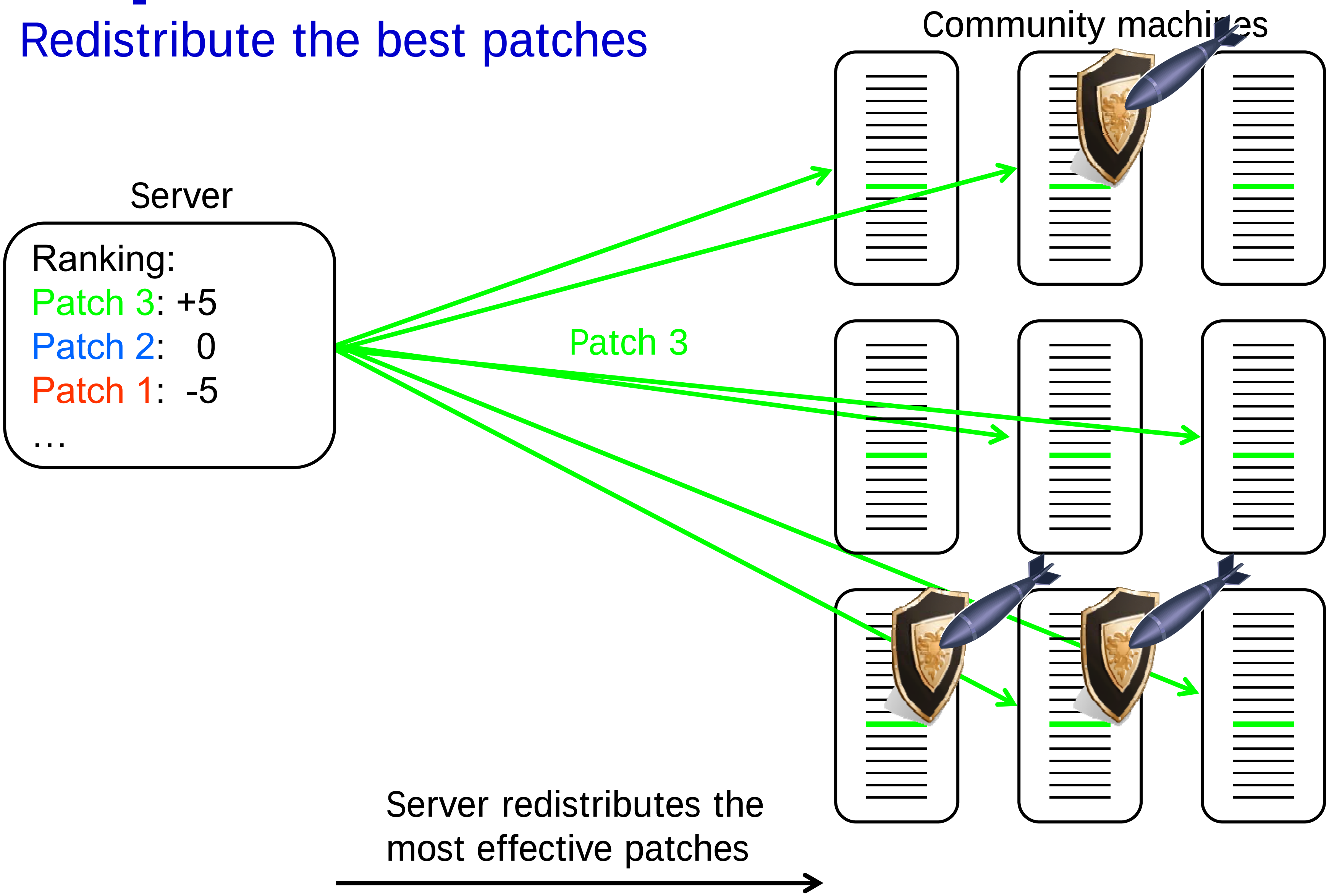
Evaluate patches

Success = no detector is triggered



Repair

Redistribute the best patches

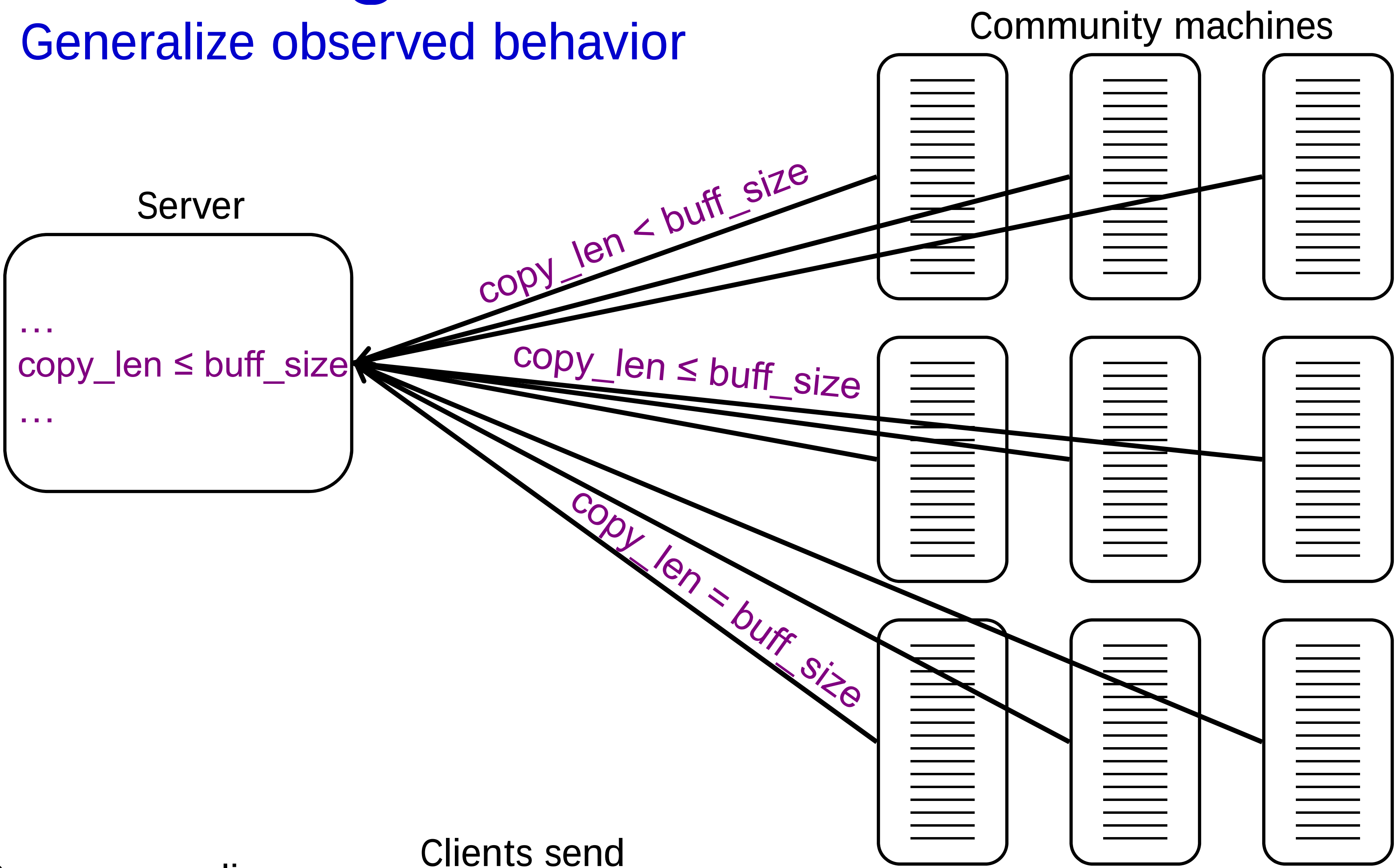


Outline

- Overview
- Learning normal behavior
- Learning attack behavior
- Repair: propose and evaluate patches
- Evaluation: adversarial Red Team exercise
- Conclusion

Learning normal behavior

Generalize observed behavior



Server generalizes (merges results)

Clients send inference results

Clients do local inference

Dynamic invariant detection

- Daikon generalizes observed program executions

Candidate constraints:

copy_len < buff_size
copy_len ≤ buff_size
copy_len = buff_size
copy_len ≥ buff_size
copy_len > buff_size
copy_len ≠ buff_size

Observation:

copy_len: 22
buff_size: 42

Remaining candidates:

copy_len < buff_size
copy_len ≤ buff_size
~~copy_len = buff_size~~
~~copy_len ≥ buff_size~~
~~copy_len > buff_size~~
copy_len ≠ buff_size

- Many optimizations for accuracy and speed
  – Data structures, code analysis, statistical tests, …
- We further enhanced the technique

Quality of inference results

- Not sound
  - Overfitting if observed executions are not representative
- Not complete
  - Templates are not exhaustive
- Useful!
- Unsoundness is not a hindrance
  - Does not affect attack detection
  - For repair, mitigated by the correlation step
  - Continued learning improves results

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Detecting attacks (or bugs)

Goal: detect problems close to their source

Code injection (Determina Memory Firewall)

- Triggers if control jumps to code that was not in the original executable

Memory corruption (Heap Guard)

- Triggers if sentinel values are overwritten

These have low overhead and no false positives

Other detectors are possible

Learning from failures

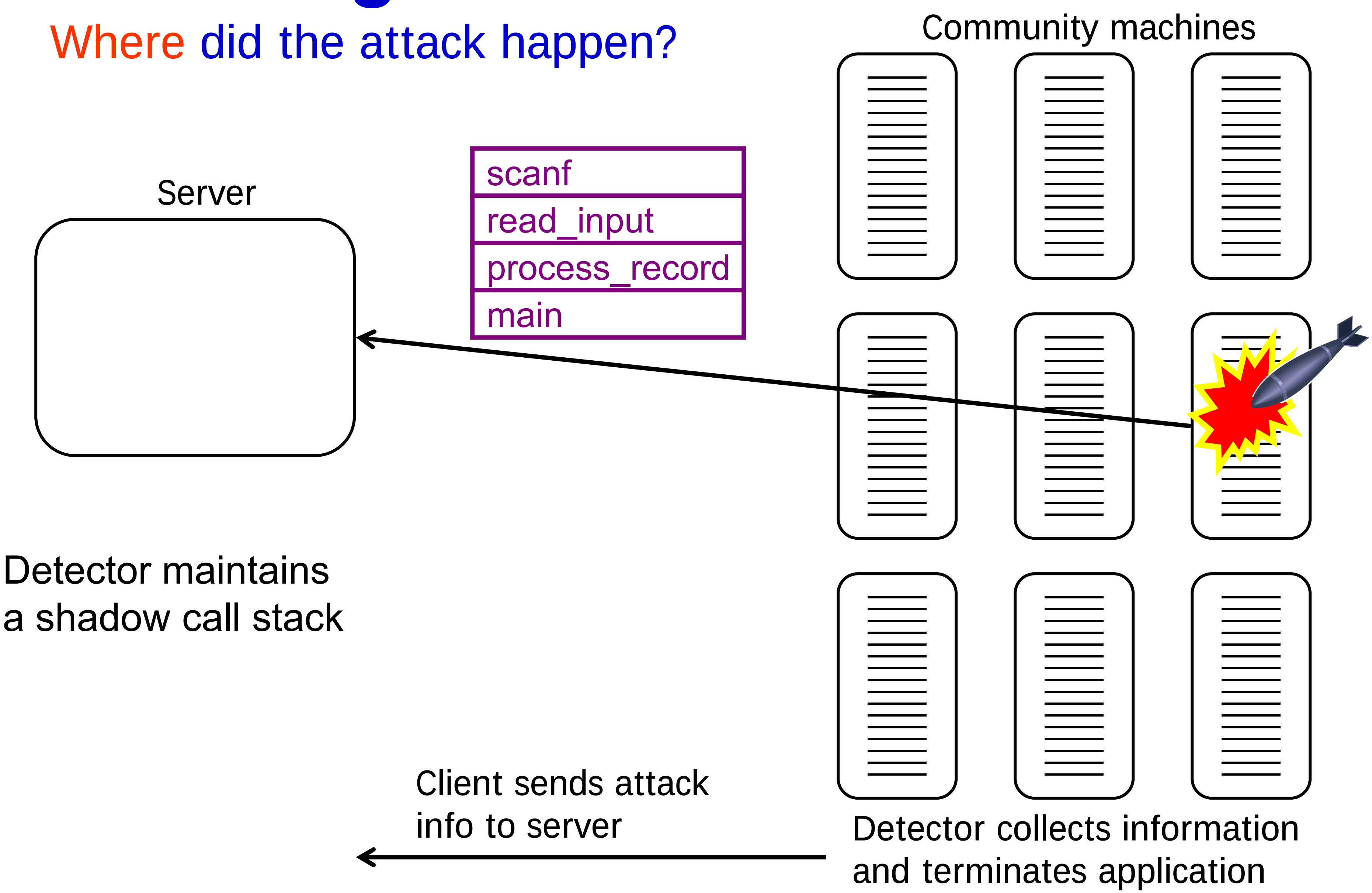
Each attack provides information about the underlying vulnerability

- That it exists
- Where it can be exploited
- How the exploit operates
- What repairs are successful

Attack detection & suppression

Learning attack behavior

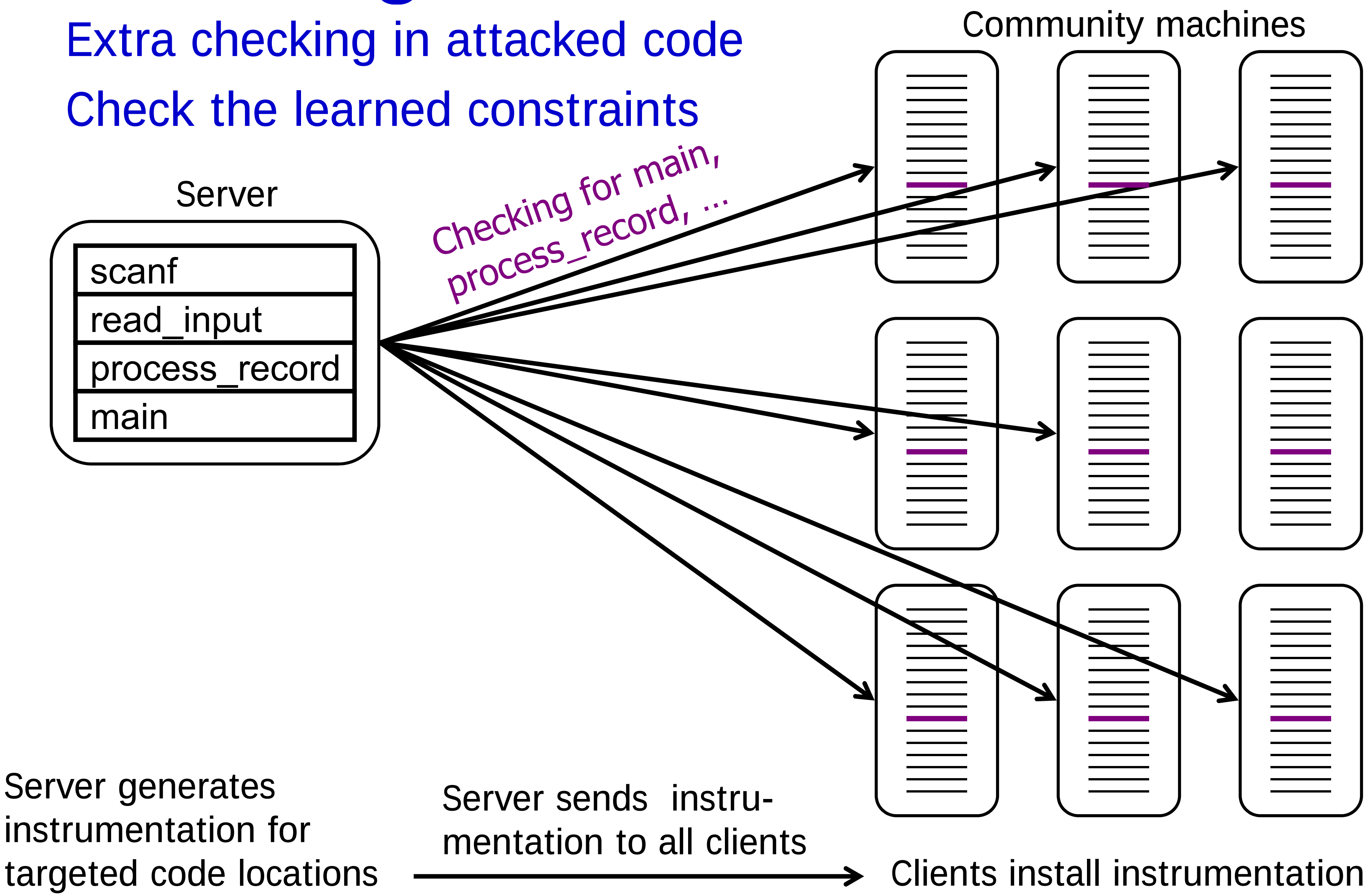
Where did the attack happen?



Learning attack behavior

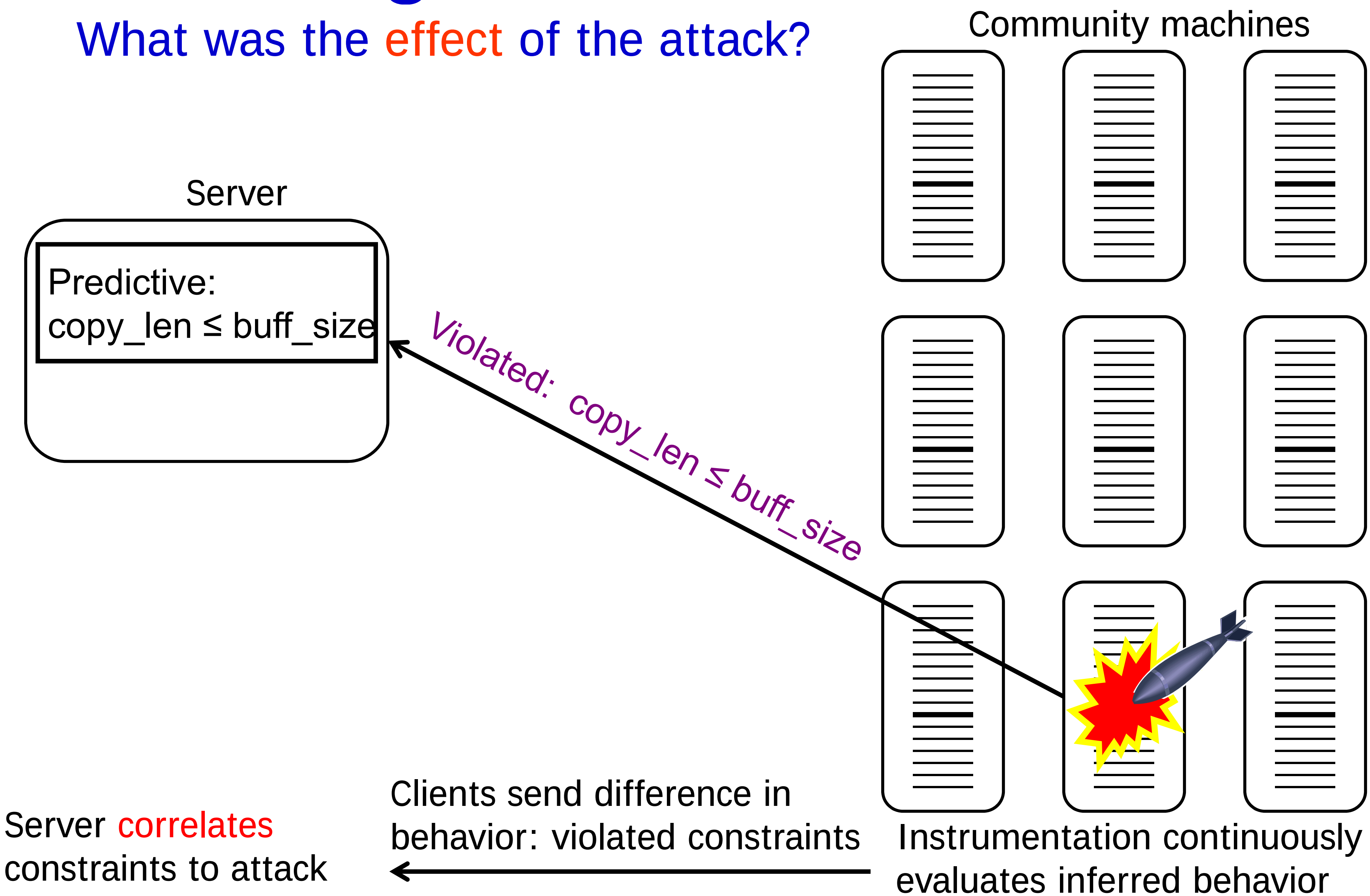
Extra checking in attacked code

Check the learned constraints



Learning attack behavior

What was the effect of the attack?



Correlating attacks & constraints

- Check constraints only at attack sites
  - – Low overhead
- A constraint is predictive of an attack if:
  - – The constraint is violated iff the attack occurs
- Create repairs for each predictive constraint
  - – Re-establish normal behavior

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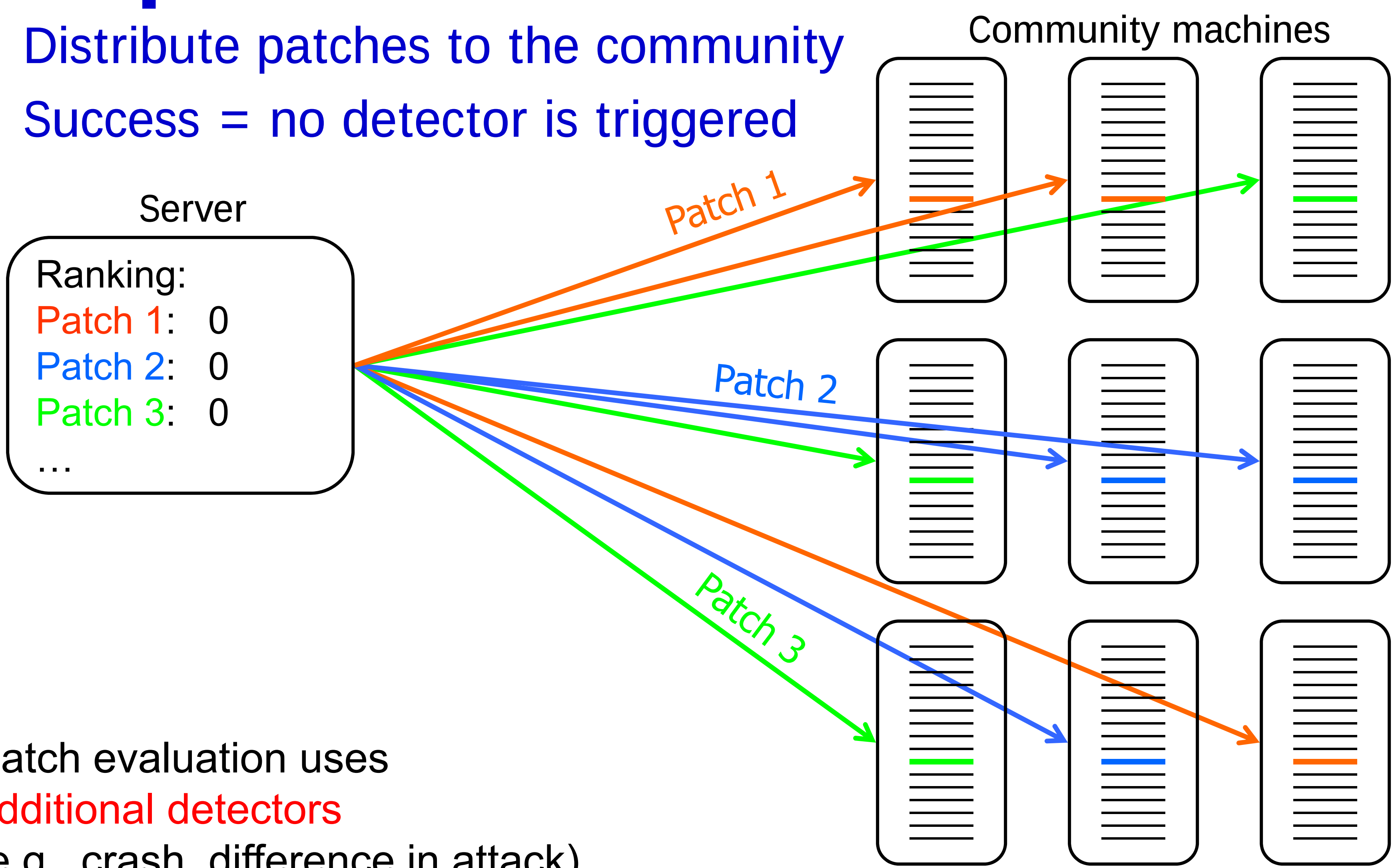
Repair

Distribute patches to the community

Success = no detector is triggered



Patch evaluation uses
additional detectors
(e.g., crash, difference in attack)

Attack example

- Target: JavaScript system routine (written in C++)
  - Casts its argument to a C++ object, calls a virtual method
  - Does not check type of the argument
- Attack supplies an "object" whose virtual table points to attacker-supplied code
- Predictive constraint at the method call:
  - JSRI address target is one of a known set
- Possible repairs:
  - Call one of the known valid methods
  - Skip over the call
  - Return early

Repair example

```
if (! (copy_len ≤ buff_size))
   copy_len = buff_size;
```

- The repair checks the predictive constraint
  - If constraint is not violated, no need to repair
  - If constraint is violated, an attack is (probably) underway
- The patch does not depend on the detector
  - Should fix the problem before the detector is triggered
- Repair is not identical to what a human would write
  - Unacceptable to wait for human response

Example constraints & repairs

$v_1 \leq v_2$

```
if (!(v₁≤v₂)) v₁ = v₂;
```

$v \geq c$

```
if (!(v≥c)) v = c;
```

$v \in \{ c_1, c_2, c_3 \}$

```
if (!(v==c₁ || v==c₂ || v==c₃)) v = cᵢ;
```

Return from enclosing procedure

```
if (!(…)) return;
```

Modify a use: convert "**`call *v`**" to

```
if (…) call *v;
```

Constraint on **`v`** (not negated)

Evaluating a patch

- In-field evaluation
  - – No attack detector is triggered
  - – No other behavior deviations
    - E.g., crash, application invariants
- Pre-validation, before distributing the patch:
  - Replay the attack
    - + No need to wait for a second attack
    - + Exactly reproduce the problem
    - – Expensive to record log; log terminates abruptly
    - – Need to prevent irrevocable effects
    - – Delays distribution of good patches
  - Run the program's test suite
    - – May be too sensitive
    - – Not available for commercial software

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Red Team

- Red Team attempts to break our system
  - Hired by DARPA; 10 engineers
- Red Team created 10 Firefox exploits
  - Each exploit is a webpage
  - Firefox executes arbitrary code
  - Malicious JavaScript, GC errors, stack smashing, heap buffer overflow, uninitialized memory

Rules of engagement

- Firefox 1.0
  - ClearView may not be tuned to known vulnerabilities
  - Focus on most security-critical components
    - No access to a community for learning
- Red Team has access to all ClearView materials
  - Source code, documents, learned invariants, …

ClearView was successful

- Detected all attacks, prevented all exploits
- For 7/10 vulnerabilities, generated a patch that maintained functionality
  - No observable deviation from desired behavior
  - After an average of 4.9 minutes and 5.4 attacks
- Handled polymorphic attack variants
- Handled simultaneous & intermixed attacks
- No false positives
- Low overhead for detection & repair

3 un-repaired vulnerabilities

Consequence: Application crashes when attacked. No exploit occurs.

1. ClearView was mis-configured: didn't try repairs in all procedures on the stack
2. Learning suite was too small: a needed constraint was not statistically significant
3. A needed constraint was not built into Daikon

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Limitations

ClearView might fail to repair an error:

- Only fixes errors for which a detector exists
- Daikon might not learn a needed constraint
- Predictive constraint may be too far from error
- Built-in repairs may not be sufficient

ClearView might degrade the application:

- Patch may impair functionality
- Attacker may subvert patch
- Malicious nodes may induce bad patches

Bottom line: Red Team tried unsuccessfully

Related work

- Attack detection: ours are mostly standard
  - Distributed: Vigilante [Costa], live monitoring [Kıcıman], statistical bug isolation [Liblit]
- Learning
  - FSMs of system calls for anomaly detection
  - Invariants: [Lin], [Demsky], Gibraltar [Baliga]
  - System configuration: FFTV [Lorenzoli], Dimmunix [Jula]
- Repair & failure tolerance
  - Checkpoint and replay: Rx [Qin], microreboot [Candea]
  - Failure-oblivious [Rinard], ASSURE [Sidiroglou]

Credits

- Saman Amarasinghe
- Jonathan Bachrach
- Michael Carbin
- Michael Ernst
- Sung Kim
- Samuel Larsen
- Carlos Pacheco
- Jeff Perkins
- Martin Rinard
- Frank Sherwood
- Stelios Sidiroglou
- Greg Sullivan
- Weng-Fai Wong
- Yoav Zibin

Subcontractor: Determina, Inc.
Funding: DARPA (PM: Lee Badger)
Red Team: SPARTA, Inc.

Contributions

ClearView: framework for patch generation

– Pluggable detection, learning, repair

1. Protects against unknown vulnerabilities
   – Learns from success
   – Learns from failure: what, where, how
   – Learning focuses effort where it is needed
2. Preserves functionality: repairs the vulnerability
3. Commercial software: Windows binaries

Evaluation via a Red Team exercise