CS 5432:

Proactive Obfuscation and Moving Target Defenses

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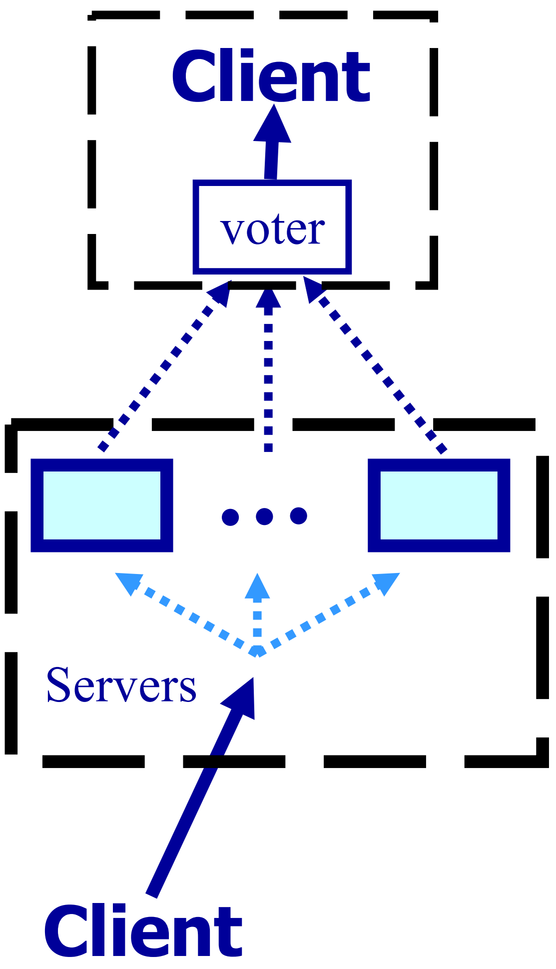
Fault-tolerance by Replication



Implements:

- Integrity
- Availability

The basic recipe …

- Servers are deterministic state machines. Clients make requests.
- Server replicas run on distinct hosts.
- Servers fail independently.
- 2t+1 servers tolerate t Byzantine

Attack-tolerance by Replication?

Assume $n = 2t + 1$ server replicas:

- Server **failures** are independent.

  Prob[$t + 1$ servers fail] = $\binom{2t+1}{t+1}$ Prob[one server fails]$^{t+1}$

- Server **vulnerabilities** present at all replicas.
  - A single attack can be used to subvert all replicas.
  - Diversity increases independence wrt attacks.

Replica Independence

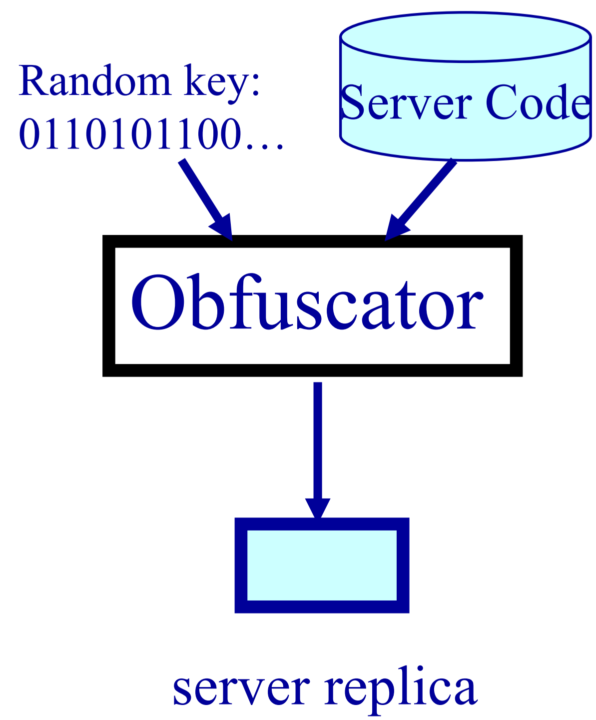
Eschewing Shared Design / Code

Solution: Diversity!

- Expensive or impossible to obtain:
  - Development costs
  - Interoperability risks

- Leverage what diversity exists.
- Mechanically create “artificial diversity”.

… Employ a program obfuscator.



Replica Independence
Proactive Recovery

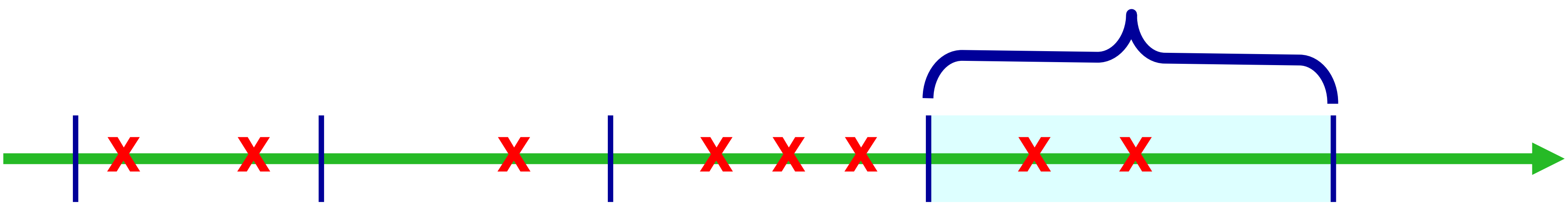
A mobile adversary can erode independence.

Idea: Proactively re-obfuscating server code defends against this:

- tolerates t compromises over *lifetime*

- versus -

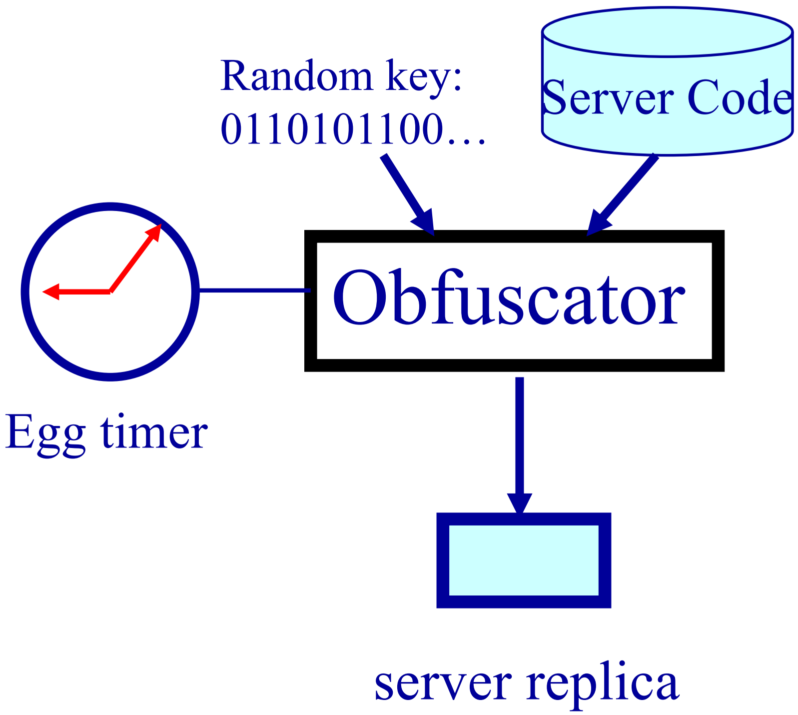
- tolerates t compromises in *window of vulnerability*



X: server compromise

Replica Independence

Implementing Proactive Obfuscation



Challenges:

- State recovery
- Protect Obfuscator
- Protect Egg-timer
- Tolerate server outage

Obfuscation: Goals and Options

Semantics-preserving random program rewriting…

Goals: Attacker does not know:

- address of specific instruction subsequences.
- address or representation scheme for variables.
- name or service entry point for any system service.

Options:

- Obfuscate source (arglist, stack layout, …).
- Obfuscate object or binary (syscall meanings, basic block and variable positions, relative offsets, …).
- All of the above.

Independence By Obfuscation?

Given program S, obfuscator computes morphs:

T(S, K1), T(S, K2), … T(S, Kn)

- Attacker knows:
  - Obfuscator T
  - Input program S
- Attacker does not know:
  - Random keys K1, K2, … Kn

    … Knowledge of the Ki would enable attackers to automate attacks!

Will an attack succeed against a **majority** of morphs?

- Seg fault likely if attack doesn't succeed.

  integrity compromise → availability compromise.

Successful Attacks on Morphs

All morphs implement the same interface.

- **Interface attacks**. Obfuscation cannot blunt attacks that exploit the semantics of that (flawed) interface.
- **Implementation attacks**. Obfuscation can blunt attacks that exploit implementation details.

Def. <u>implementation attack</u>: An input for which all morphs (in some given set) don't **all** produce the same output.

Replica Independence

Effectiveness of Obfuscation

Ultimate Goal: Determine the probability that a majority of morphs generate the same output for a set of attacks?

Modest goal: Understand how effective obfuscation is as compared with other defenses?

- Obvious candidate: Type checking

Replica Independence

Type Checking as a Defense

Type checking: Process to establish that all executions satisfy certain properties.

- Static: Checks made prior to exec.
  - Requires a decision procedure
- Dynamic: Checks made as exec proceeds.
  - Requires adding checks. Exec aborted if violated.

Probabilistic dynamic type checking: Some checks are skipped on a random basis.

Theory → Practice

Putting it Together: CoPrOF

Cornell Proactive Obfuscation Firewall

Specification:

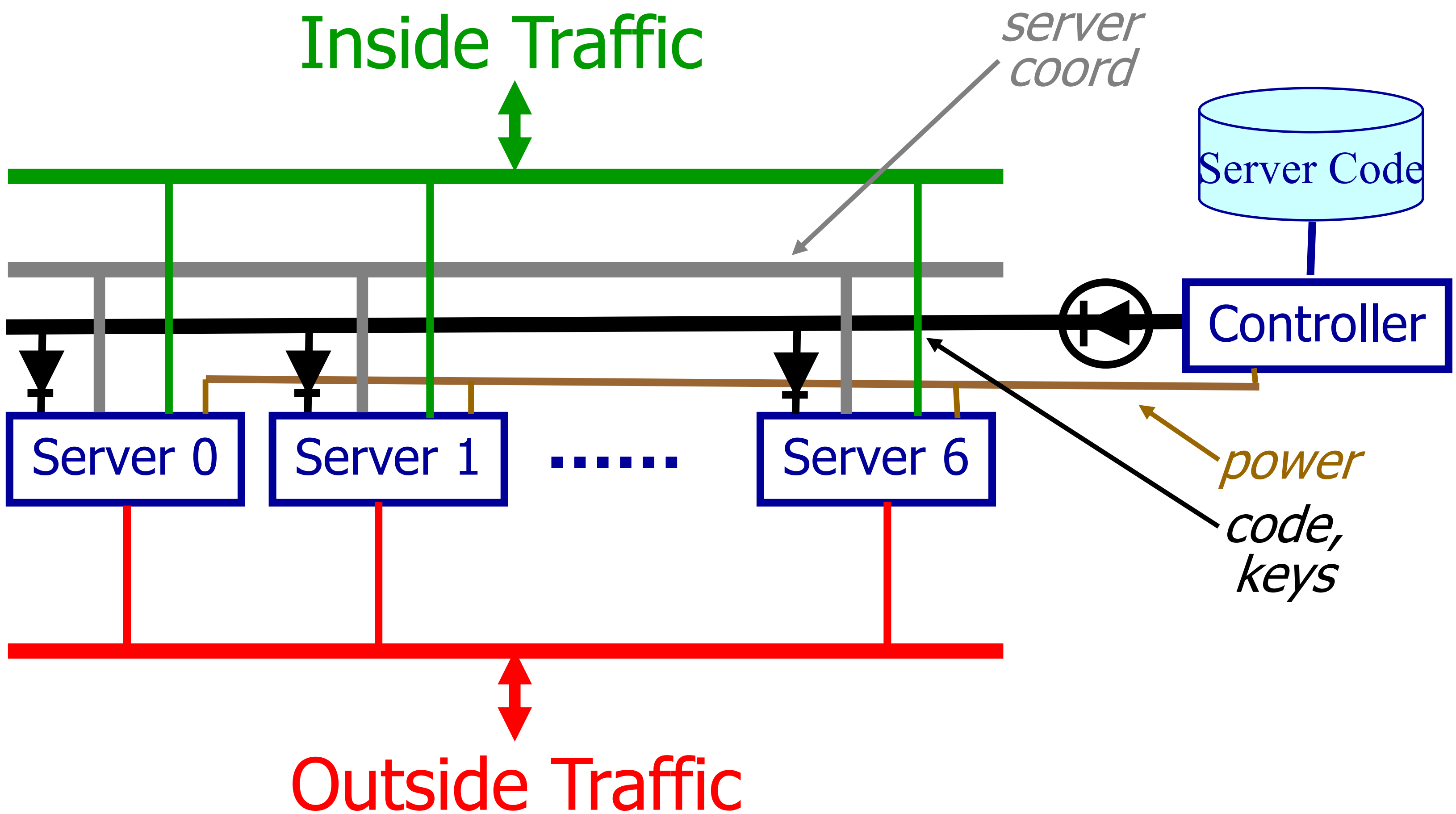
- Unlikely that attacker can gain control of the service.
- A steady stream of attacks might block service. (But service is restored once that stream is terminated.)

Server:

- Receives messages from “outside”.
- Manages state (encodes history of messages seen).
- Forward subset of messages to “inside”.

Theory → Practice

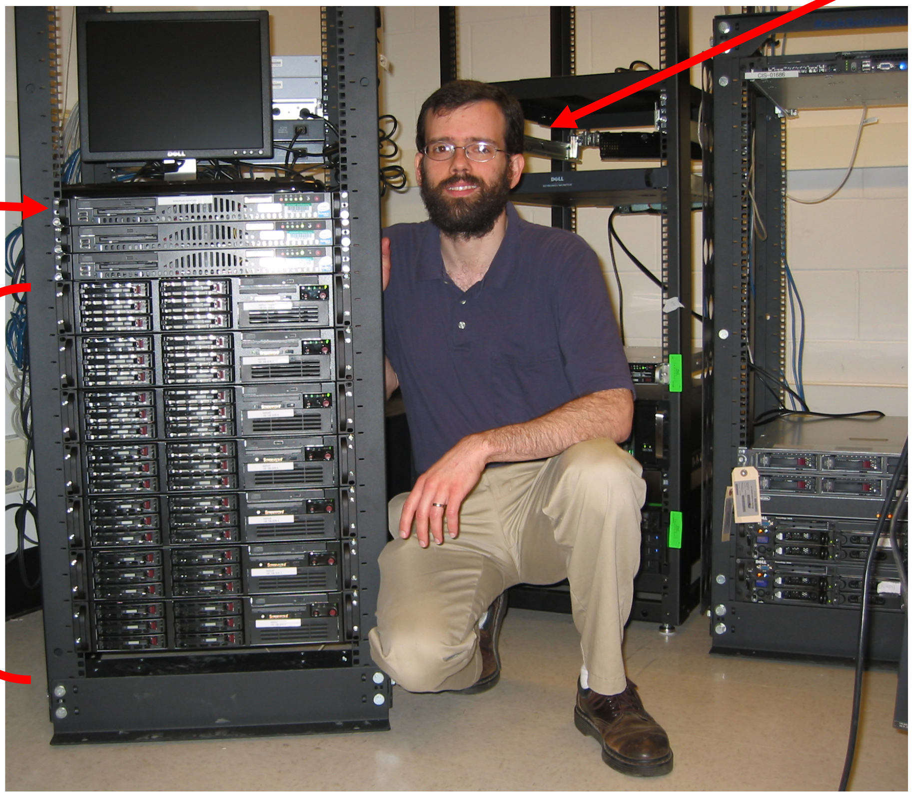
CoPrOF: Prototype



N = 7 = 3(t+1) + 1 servers

Theory → Practice

CoPrOF: In the Flesh



<u>Processors:</u>

3 GHz Pentium 4

OpenBSD 4.0

Theory → Practice
CoPrOF Replica Operation

Controller:

- toggle power to reboot each server.
- Rebuilds image with obfuscation: re-numbers kernel calls (5 min!).
- transmits PXE boot and private keys to a rebooting server.
- broadcasts new public key certificate to all servers.

When server replica is powered on:

- Issues PXE boot request via network card.
- Awaits receipt of new image and priv keys.
- New image executes:
  - requests current state
  - votes on states it receives
    - PFsync basis to send and receive state.
  - starts processing packets (UCB Packet Filter PF)

Theory → Practice

Server Replica Agreement

Every sequence number has a <u>master</u>.

- Master selects an unprocessed message.
- Runs Byz PAXOS to ensure all replicas agree.
- All non-faulty replicas process that msg.

<u>Master</u> for seqno s:

- **Def**: M(s) = s mod 7
- **Master for s**: smallest non-faulty successor of M(s).
  non-faulty p: p did not fail a timeout test for seqno s.

Theory → Practice

Server Output Protocol

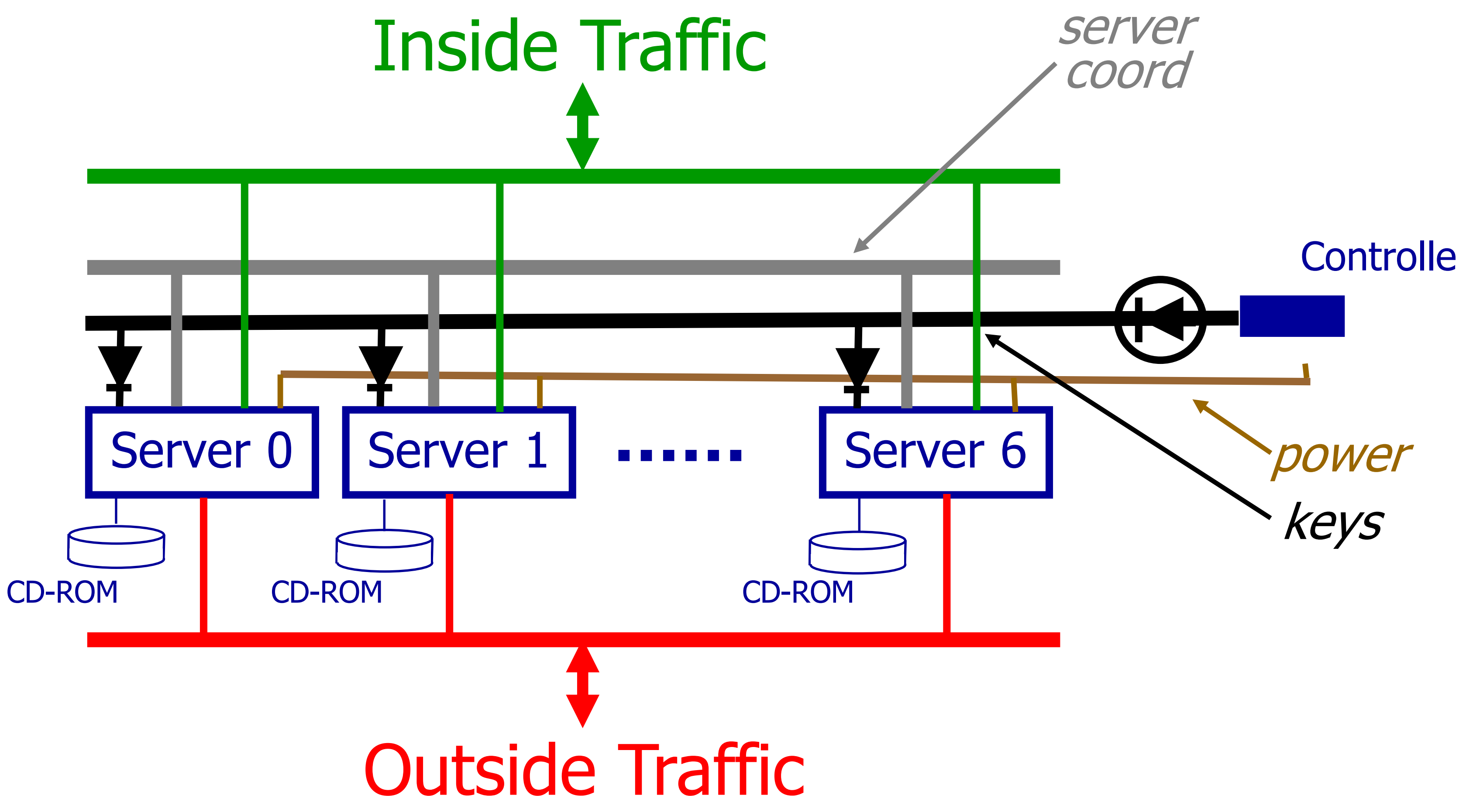
- Each CoPrOF host outputs msg with partial sigs.
- Client assembles t+1 partial sigs to obtain signed output of PF.

Alternative (so no client modification required):

- Replicas broadcast partial sigs to each other.
- Replicas assemble partial signatures and send to client.
  - Client can check if signature is correct.
  - Client does receive duplicate messages.
    - Replica snooping can suppress duplicate transmission.

Theory → Practice

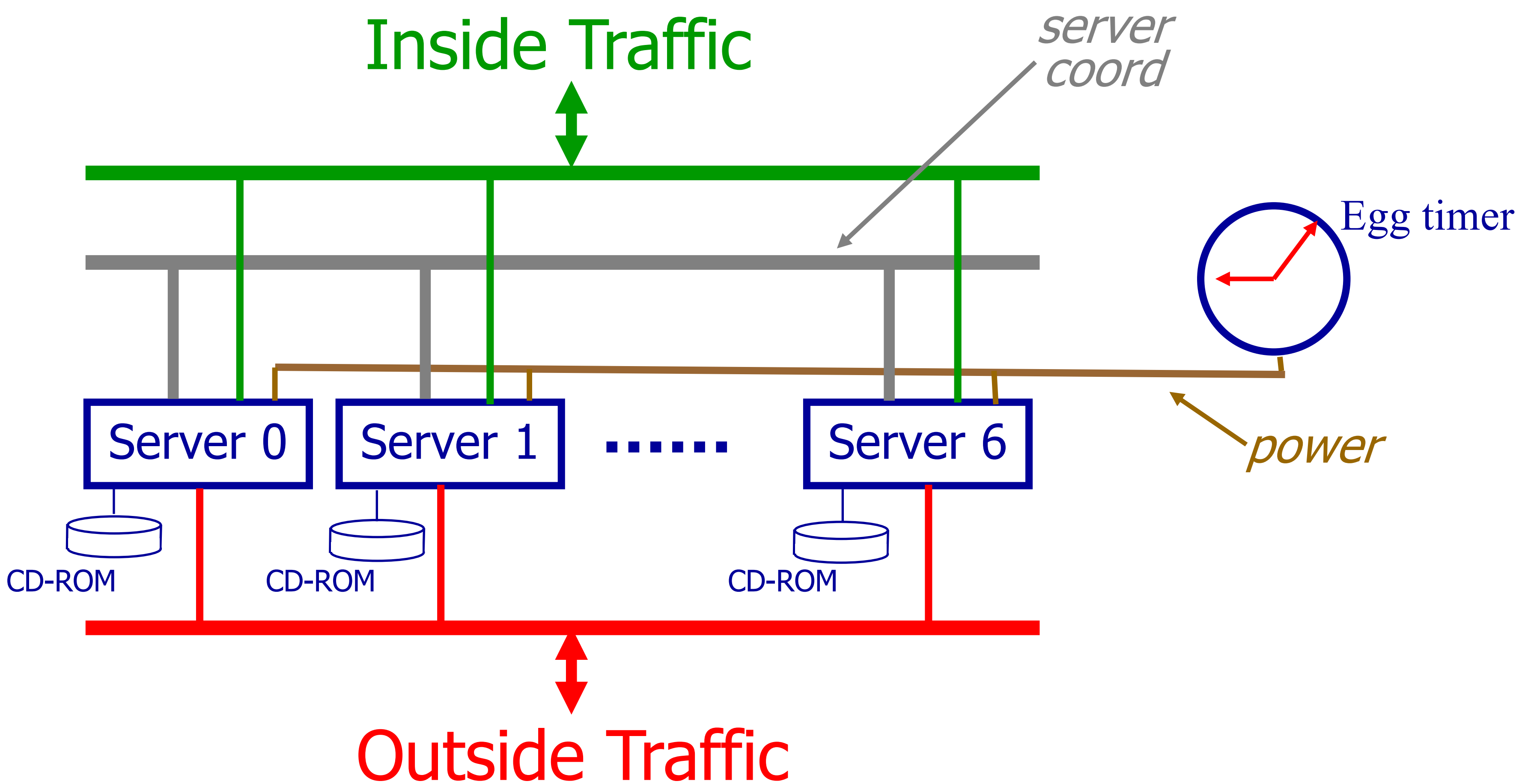
CoPrOF: 2nd Generation Prototype



N = 7 = 3(t+1) + 1 servers

Theory → Practice

CoPrOF: Ultimate Prototype



N = 7 = 3(t+1) + 1 servers

From 30,000 feet…

(What we really did)

Diversity as a Defense

Create independence from diversity.

- Independence increases the cost to attackers, since attacks against one component do not compromise another.

Forms of diversity:

- Static diversity ("in space").
- Dynamic diversity ("in time").
  - Also known as: "moving target defense"
  - Adds uncertainty for attackers, due to changes in system.
  - Can refresh [amplify] static diversity (e.g., proactive obfuscation).

Diversity Challenges

- Differences in interface:
  - Requires clients to adapt.
- Differences in internals but not interface:
  - Does not defend against exploits that leverage problematic interface semantics.
    - … Therefore: only defends against internal logic errors or under-specification.
  - Could require state migration or translation.

Why Attacks Work

- Some attacks are facilitated by information.
  - Brute force analysis (off-line / on-line).
  - Discovered by recon.

… Period of preparation. Then able to attack.

Moving target defense invalidates preparation.

- Some attacks exploit idiosyncratic technical details.
  - Specific behaviors when "underspecified operation" attempted are not available to attacker if those details change.
  - Changing the interpretation of "underspecified" blocks attacks that depend on that semantics.

Design of Moving Target Defenses

- What to move?
  - Must change some aspect of system that is used by attacker.
- How to move?
  - May require distinguishing "self" from "other."
- When to move
  - Reactive: Based on system event, possibly attacker-caused.
  - Proactive: At fixed or random intervals.

Diversification techniques 1

Processor Storage

- Address space layout randomization (ASLR)
- Heap layout randomization
- Stack layout
  - Variable reordering on run-time stack
    - Can’t re-order fields within a variable.
  - Change direction of stack growth (e.g. support upward growth).
  - Stack frame padding.
- Register name randomization
  - Only some registers can be renamed
- Data representation (e.g., XOR with some key)
  - Values
  - Addresses (e.g., return pointers)

Diversification techniques 2

Processor Instructions

- Interface:
  - Instruction set randomization (ISR)
  - System call number randomization.
  - Library location/name randomization.
- Internals
  - Optimize code (or not)

Diversification techniques 3

System Level

- Network IP address, port, protocol
  - Port hopping (like spread spectrum comm)
- Virtual Machine
- Software stack / components

ISR Details

ISR defends against code-injection attacks, but does not work against attacks in data (e.g., attacks delivered as scripts).

- All binaries are pre-randomized when stored on disk.
  - Creates a randomly-mutating exec env whose language is not known to attackers
  - Attempts to guess code locations are hindered by mutating the env.
- Do randomization when binary is loaded and stored on disk.
- To de-randomize, need to know about context switches and calls, so correct key can be found for target of xfer.
- HW-based ISR: Hardware does xor on instruction fetch.
- SW-based ISR: Use binary translation.

How Attackers Bypass ISR

- Guess the key
- Get key using known plaintext attack…
  - Feasible for 16 bit XOR encrypt but not for AES encrypt
  - Best not to allow an attacker to export a binary in library or file sys
- Attacker finds another interpreter (e.g., uses another shell) that does not employ ISR.
  - Hard for sys owner to have found and fixed all interpreters.

Overcoming Diversity Defense

- Attacker: Use the full system rather than adding to it.
  - Use existing instructions to circumvent ISR.
  - Use existing storage to circumvent ASLR.
  - Recruit a "confused deputy" to perform operations.

- Attacker: Design attacks that work in many system variants (transcending diversity).
  - Use of a NOP sled to overcome uncertainty in memory layout when doing buffer overflow attack.