CSE 454

Security III

"Outbreak!"

Internet Outbreaks: Epidemiology and Defenses

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Collaborative Center for Internet Epidemiology and Defenses (CCIED)

- Joint project (UCSD/ICSI)
  - Other PIs: Vern Paxson, Nick Weaver, Geoff Voelker, George Varghese
  - ~15 staff and students in addition
  - Funded by NSF with additional support from Microsoft, Intel, HP, and UCSD’s CNS
- Three key areas of interest
  - Infrastructure and analysis for understanding large-scale Internet threads
  - Automated defensive technologies
  - Forensic and legal requirements

How Chicken Little sees the Internet...

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Why Chicken Little is a naïve optimist

- Imagine the following species:
  - Poor genetic diversity; heavily inbred
  - Lives in "hot zone"; thriving ecosystem of infectious pathogens
  - Instantaneous transmission of disease
  - Immune response 10-1M times slower
  - Poor hygiene practices
- What would its long-term prognosis be?
  - What if diseases were designed...
    - Trivial to create a new disease
    - Highly profitable to do so

Threat transformation

- Traditional threats
  - Attacker manually targets high-value system/resource
  - Defender increases cost to compromise high-value systems
  - Biggest threat: insider attacker
- Modern threats
  - Attacker uses automation to target all systems at once (can filter later)
  - Defender must defend all systems at once
  - Biggest threats: software vulnerabilities & naïve users
Large-scale technical enablers

- **Unrestricted connectivity**
  - Large-scale adoption of IP model for networks & apps

- **Software homogeneity & user naiveté**
  - Single bug = mass vulnerability in millions of hosts
  - Trusting users (“ok”) = mass vulnerability in millions of hosts

- Few meaningful defenses
- Effective anonymity (minimal risk)

Driving Economic Forces

- No longer just for fun, but for profit
  - SPAM forwarding (MyDoom.A backdoor, SoBig), Credit Card theft (Korgo), DDoS extortion, etc...
  - Symbiotic relationship: worms, bots, SPAM, etc
  - Fluid third-party exchange market (millions of hosts for sale)
    - Going rate for SPAM proxying 3-10 cents/host/week
    - Seems small, but 25k botnet gets you $40k-130k/yr
  - Generalized search capabilities are next

  - “Virtuous” economic cycle
  - The bad guys have large incentive to get better

Today’s focus: Outbreaks

- Outbreaks?
  - Acute epidemics of infectious malcode designed to actively spread from host to host over the network
  - E.g. Worms, viruses (ignore pedantic distinctions)

- Why epidemics?
  - Epidemic spreading is the fastest method for large-scale network compromise

- Why fast?
  - Slow infections allow much more time for detection, analysis, etc (traditional methods may cope)

Was Slammer really fast?

- **Yes**, it was orders of magnitude faster than CR
- **No**, it was poorly written and unsophisticated
- **Who cares?** It is literally an academic point
  - The current debate is whether one can get < 500ms
  - **Bottom line**: way faster than people!

How to think about worms

- Reasonably well described as infectious epidemics
  - Simplest model: Homogeneous random contacts
    - Classic SI model
      - N: population size
      - S(t): susceptible hosts at time t
      - I(t): infected hosts at time t
      - β: contact rate
      - δ: infection rate
      - \( i(t) = e^{\beta t} \)
      - \( \beta = \frac{\delta}{1 - e^{-\delta t}} \)


- First ~1min behaves like classic random scanning worm
  - Doubling time of ~8.5 seconds
  - CodeRed doubled every 40mins

- >1min worm starts to saturate access bandwidth
  - Some hosts issue >20,000 scans per second
  - Self-interfering (no congestion control)

- Peaks at ~3min
  - >$5 million IP scans/sec

- 90% of Internet scanned in <10mins
  - Infected ~100k hosts (conservative)

What's important?

- There are lots of improvements to the model…
  - Chen et al, Modeling the Spread of Active Worms, Infocom 2003 (discrete time)
  - Wang et al, Modeling Timing Parameters for Virus Propagation on the Internet, ACM WORM ’04 (delay)
  - Ganesh et al, The Effect of Network Topology on the Spread of Epidemics, Infocom 2006 (topology)
- … but the bottom line is the same. We care about two things:
  - How likely is it that a given infection attempt is successful?
    - Target selection (random, biased, hillist, topological,…)
    - Vulnerability distribution (e.g. density – S(0)/N)
  - How frequently are infections attempted?
    - $\beta$: Contact rate

What can be done?

- Reduce the number of susceptible hosts
  - Prevention, reduce $S(t)$ while $I(t)$ is still small
    - (ideally reduce $S(0)$)
- Reduce the contact rate
  - Containment, reduce $\beta$ while $I(t)$ is still small

Prevention: Software Quality

- **Goal:** eliminate vulnerability
- Static/dynamic testing (e.g. Cowan, Wagner, Engler, etc)
- Software process, code review, etc.
- Active research community
  - Taken seriously in industry
    - Security code review alone for Windows Server 2003 ~ $200M
- Traditional problems: soundness, completeness, usability
- Practical problems: scale and cost

Prevention: Software Heterogeneity

- **Goal:** reduce impact of vulnerability
  - Use software diversity to tolerate attack
    - Exploit existing heterogeneity
    - Junqueria et al, Surviving Internet Catastrophes, USENIX ’05
    - Create Artificial heterogeneity (hot topic)
      - Forrest et al, Building Diverse Computer Systems, HotOS ’97
      - Large contemporary literature
  - Open questions: class of vulnerabilities that can be masked, strength of protection, cost of support

Prevention: Software Updating

- **Goal:** reduce window of vulnerability
  - Most worms exploit known vulnerability (1 day -> 3 months)
  - Window shrinking: automated patch->exploit
  - Patch deployment challenges, downtime, Q/A, etc
  - Ressorla, Is finding security holes a good idea?, WEIS ’04
  - Network-based filtering: decouple "patch" from code
    - E.g. TCP packet to port 1434 and > 60 bytes
  - Wang et al, Shield: Vulnerability-Driven Network Filters for Preventing Known Vulnerability Exploits, SIGCOMM ’04
  - Symantec: Generic Exploit Blocking
  - Automated patch creation: fix the vulnerability on-line
    - Bidroghou et al, Building a Reactive Immune System for Software Services, USENIX ’05
  - Anti-worms: block the vulnerability and propagate
    - Castaneda et al, WormWORM: Preliminary Study of an Active counter-Attack Mechanism, WORM ’04

Prevention: Hygiene Enforcement

- **Goal:** keep susceptible hosts off network
  - Only let hosts connect to network if they are "well cared for"
    - Recently patched, up-to-date anti-virus, etc…
  - Automated version of what they do by hand at NSF
  - Cisco Network Admission Control (NAC)
What can be done?

- Reduce the number of susceptible hosts
  - **Prevention**, reduce $S(t)$ while $I(t)$ is still small (ideally reduce $S(0)$)

- Reduce the contact rate
  - **Containment**, reduce $\beta$ while $I(t)$ is still small

Containment

- Reduce contact rate
  - Slow down
  - Throttle connection rate to slow spread
    - Twycross & Williamson, Implementing and Testing a Virus Throttle, USENIX Sec '03
    - Important capability, but worm still spreads...
  - Quarantine
    - Detect and block worm

Defense requirements

- We can define reactive defenses in terms of:
  - **Reaction time** – how long to detect, propagate information, and activate response
  - **Containment strategy** – how malicious behavior is identified and stopped
  - **Deployment scenario** - who participates in the system

- Given these, what are the engineering requirements for any effective defense?

Methodology

- Simulate spread of worm across Internet topology
  - Infected hosts attempt to spread at a fixed rate (probes/sec)
  - Target selection is uniformly random over IPv4 space

- Source data
  - Vulnerable hosts: 359,000 IP addresses of CodeRed v2 victims
  - Internet topology: AS routing topology derived from RouteViews

- Simulation of defense
  - System detects infection within reaction time
  - Subset of network nodes employ a containment strategy

- Evaluation metric
  - % of vulnerable hosts infected in 24 hours
  - 100 runs of each set of parameters (95th percentile taken)
  - Systems must plan for reasonable situations, not the average case

  See: Moore et al, Internet Quarantine: Requirements for Containing Self-Propagating Code, Infocom 2003 for more details

Naïve model: Universal deployment

- Assume every host employs the containment strategy

- Two containment strategies :
  - **Address filtering**:
    - Block traffic from malicious source IP addresses
    - Reaction time is relative to each infected host
    - MUCH easier to implement
  - **Content filtering**:
    - Block traffic based on signature of content
    - Reaction time is from first infection

- How quickly does each strategy need to react?
- How sensitive is reaction time to worm probe rate?

How quickly does each strategy need to react?

- To contain worms to 10% of vulnerable hosts after 24 hours of spreading at 10 probes/sec (CodeRed-like):
  - Address filtering: reaction time must be < 25 minutes.
  - Content filtering: reaction time must be < 3 hours
**How sensitive is reaction time to worm probe rate?**

- Reaction times must be fast when probe rates get high:
  - 10 probes/sec: reaction time must be < 3 hours
  - 1000 probes/sec: reaction time must be < 2 minutes

**Limited network deployment**

- Depending on **every** host to implement containment is probably a bit optimistic:
  - Installation and administration costs
  - System communication overhead

- A more realistic scenario is **limited** deployment in the network:
  - **Customer Network:** firewall-like inbound filtering of traffic
  - **ISP Network:** traffic through border routers of large transit ISPs

- How effective are the deployment scenarios?
- How sensitive is reaction time to worm probe rate under limited network deployment?

**How effective are the deployment scenarios?**

**How sensitive is reaction time to worm probe rate?**

- Above 60 probes/sec, containment to 10% hosts within 24 hours is **impossible** for top 100 ISPs even with **instantaneous** reaction.

**Defense requirements summary**

- **Reaction time**
  - Required reaction times are a couple minutes or less for CR-style worms (seconds for worms like Slammer)

- **Containment strategy**
  - Content filtering is far more effective than address blacklisting for a given reaction speed

- **Deployment scenarios**
  - Need nearly all customer networks to provide containment
  - Need at least top 40 ISPs provide containment; top 100 ideal

- **Is this possible?** Let’s see…

**Outbreak Detection/Monitoring**

- **Two classes of detection**
  - **Scan detection:** detect that host is infected by infection attempts
  - **Signature inference:** automatically identify content signature for exploit (sharable)

- **Two classes of monitors**
  - Ex-situ: “canary in the coal mine”
    - **Network Telescopes**
    - **HoneyNets/Honeypots**
  - In-situ: real activity as it happens
Network Telescopes

- Infected host scans for other vulnerable hosts by randomly generating IP addresses
- Network Telescope: monitor large range of unused IP addresses – will receive scans from infected host
- Very scalable. UCSD monitors 17M+ addresses

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Telescopes + Active Responders

- Problem: Telescopes are passive, can’t respond to TCP handshake
  - Is a SYN from a host infected by CodeRed or Welchia? Dunno.
  - What does the worm payload look like? Dunno.
- Solution: proxy responder
  - Stateless: TCP SYNACK (Internet Motion Sensor), per-protocol responders (iSink)
  - Stateful: Honeyd
  - Can differentiate and fingerprint payload
    - False positives generally low since no regular traffic

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HoneyNets

- Problem: don’t know what worm/virus would do? No code ever executes after all.
- Solution: redirect scans to real “infectable” hosts (honeypots)
  - Individual hosts or VM-based: Collapsar, HoneyStat, Symantec
  - Can reduce false positives/negatives with host-analysis (e.g. TaintCheck, Vigilante, Minos) and behavioral/procedural signatures
- Challenges
  - Scalability
  - Liability (honeywall)
  - Isolation (2000 IP addrs -> 40 physical machines)
  - Detection (VMWare detection code in the wild)

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The Scalability/Fidelity tradeoff

- Most Scalable
- Highest Fidelity

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New CCIED project: large scale high-fidelity honeyfarm

- Goal: emulate significant fraction of Internet hosts (1M)
- Multiplex large address space on smaller # of servers
  - Temporal & spatial multiplexing
- Physical Honeyfarm Servers
- Potemkin VMM: large #’s VMs/host
  - Delta Virtualization: copy-on-write VM image
  - Flash Cloning: on-demand VM (<1ms)

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Overall limitations of telescope, honeynet, etc monitoring

- Depends on worms scanning it
  - What if they don’t scan that range (smart bias)
  - What if they propagate via e-mail, IM?
- Inherent tradeoff between liability exposure and detectability
  - Honeypot detection software exists
- It doesn’t necessary reflect what’s happening on your network (can’t count on it for local protection)
- Hence, we’re always interested in native detection as well

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Scan Detection

- Idea: detect worm's infection attempts
  - In the small: ZoneAlarm, but how to do in the network?

- Indirect scan detection
  - Wong et al., A Study of Mass-mailing Worms, WORM '04
  - Whyte et al., DNS-based Detection of Scanning Worms in an Enterprise Network, NDSS '05

- Direct scan detection
  - Weaver et al., Very Fast Containment of Scanning Worms, USENIX Sec '04
  - Threshold Random Walk – bias source based on connection success rate (Jung et al.), use approximate state for fast hardware implementation
  - Can support multi-Gigabit implementation, detect scan within 10 attempts
  - Few false positives: Gnutella (finding accessing), Windows File Sharing (benign scanning)
  - Venkataraman et al., New Streaming Algorithms for Fast Detection of Superspreaders, just recently

Signature inference

- Challenge: need to automatically learn a content “signature” for each new worm – potentially in less than a second!

- Singh et al., Automated Worm Fingerprinting, OSDI '04
- Kim et al., Autograph: Toward Automated, Distributed Worm Signature Detection, USENIX Sec '04

Approach

- Monitor network and look for strings common to traffic with worm-like behavior
- Signatures can then be used for content filtering

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Content sifting

- Assume there exists some (relatively) unique invariant bitstring $W$ across all instances of a particular worm (true today, not tomorrow...)
- Two consequences
  - Content Prevalence: $W$ will be more common in traffic than other bitstrings of the same length
  - Address Dispersion: the set of packets containing $W$ will address a disproportionate number of distinct sources and destinations
- Content sifting: find $W$'s with high content prevalence and high address dispersion and drop that traffic

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The basic algorithm

```plaintext
A ➔ B

Prevalence Table

Address Dispersion Table

Sources Destinations

1

1 (A) 1 (B)
```
The basic algorithm

Address Dispersion Table

Sources       Destinations
1 (A) 1 (B)
1 (C) 1 (A)

Prevalence Table
1 1

Kim et al's solution: Autograph

- Pre-filter flows for those that exhibit scanning behavior (i.e. low TCP connection ratio)
  - HUGE reduction in input, fewer prevalent substrings
  - Don’t need to track dispersion at all
  - Fewer possibilities of false positives

- However, only works with TCP scanning worms
  - Not UDP (Slammer), e-mail viruses (MyDoom), IM-based worms (Bizex), P2P (Benjamin)


Challenges

- Computation
  - To support a 1Gbps line rate we have 12us to process each packet
    - Dominated by memory references; state expensive
    - Content sifting requires looking at every byte in a packet

- State
  - On a fully-loaded 1Gbps link a naïve implementation can easily consume 100MB/sec for tables

Which substrings to index?

- Approach 1: Index all substrings
  - Way too many substrings → too much computation → too much state

- Approach 2: Index whole packet
  - Very fast but trivially evadable (e.g., Witty, Email Viruses)

- Approach 3: Index all contiguous substrings of a fixed length ‘S’
  - Can capture all signatures of length ‘S’ and larger

A B C D E F G H I J K
How to represent substrings?

- Store hash instead of literal to reduce state
- Incremental hash to reduce computation
- Rabin fingerprint is one such efficient incremental hash function [Rabin81, Manber94]
  - One multiplication, addition and mask per byte

P1: R A N D O M
Fingerprint = 11000000

P2: R A N D O M
Fingerprint = 11000000

How to subsample?

- Approach 1: sample packets
  - If we chose 1 in N, detection will be slowed by N
- Approach 2: sample at particular byte offsets
  - Susceptible to simple evasion attacks
  - No guarantee that we will sample same sub-string in every packet
- Approach 3: sample based on the hash of the substring

Value sampling [Manber '94]

- Sample hash if last 'N' bits of the hash are equal to the value 'V'
  - The number of bits 'N' can be dynamically set
  - The value 'V' can be randomized for resiliency

A B C D E F G H I J K
Fingerprint = 11000000
SAMPLE

- \( P_{\text{track}} \rightarrow \) Probability of selecting at least one substring of length \( S \) in a \( L \) byte invariant
  - For 1/64 sampling (last 6 bits equal to 0), and 40 byte substrings
  - \( P_{\text{track}} = 99.64\% \) for a 400 byte invariant

Efficient high-pass filters for content

- Only want to keep state for prevalent substrings
- Chicken vs egg: how to count strings without maintaining state for them?

- Multi Stage Filters: randomized technique for counting "heavy hitter" network flows with low state and few false positives [Estan02]
  - Instead of using flow id, use content hash
  - Three orders of magnitude memory savings

Finding “heavy hitters” via Multistage Filters

- Field Extraction
- Comparator
- Counters
- Increment
- Hash 1
- Hash 2
- Hash 3
- Stage 1
- Stage 2
- Stage 3
- ALERT! if all counters above threshold

Observation:

High-prevalence strings are rare

Only 0.6% of the 40 byte substrings repeat more than 3 times in a minute
Multistage filters in action

Grey = other hashes
Yellow = rare hash
Green = common hash

Stage 1
- Counters
- Threshold

Stage 2

Stage 3

Observation:
High address dispersion is rare too

- Naïve implementation might maintain a list of sources (or destinations) for each string hash
- But dispersion only matters if its over threshold
  - Approximate counting may suffice
  - Trades accuracy for state in data structure
- Scalable Bitmap Counters
  - Similar to multi-resolution bitmaps [Estan03]
  - Reduce memory by 5x for modest accuracy error

Scalable Bitmap Counters

- Hash : based on Source (or Destination)
- Sample : keep only a sample of the bitmap
- Estimate : scale up sampled count
- Adapt : periodically increase scaling factor

Error Factor = 2/(2^{numBitmaps}-1)
- With 3, 32-bit bitmaps, error factor = 28.5%

Content sifting summary

- Index fixed-length substrings using incremental hashes
- Subsample hashes as function of hash value
- Multi-stage filters to filter out uncommon strings
- Scalable bitmaps to tell if number of distinct addresses per hash crosses threshold
- Now its fast enough to implement

Software prototype: Earlybird

Setup 1: Large fraction of the UCSD campus traffic, Traffic mix: approximately 5000 end-hosts, dedicated servers for campus wide services (DNS, Email, NFS etc.) Line-rate of traffic varies between 100 & 500Mbps.

Setup 2: Fraction of local ISP Traffic, Traffic mix: dialup customers, leased-line customers Line-rate of traffic is roughly 100Mbps.

Content Sifting in Earlybird

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Content sifting overhead

- Mean per-byte processing cost
  - 0.409 microseconds, without value sampling
  - 0.042 microseconds, with 1/64 value sampling (~60 microseconds for a 1500 byte packet, can keep up with 200Mbps)
- Additional overhead in per-byte processing cost for flow-state maintenance (if enabled):
  - 0.042 microseconds

Experience

- Generally... ahem... good.
- Detected and automatically generated signatures for every known worm outbreak over eight months
- Can produce a precise signature for a new worm in a fraction of a second
- Known worms detected:
  - Code Red, Nimda, WebDav, Slammer, Opaserv, ... 
- Unknown worms (with no public signatures) detected:
  - MsBlaster, Bagle, Sasser, Kibvu, ...

Sasser

- Slower spread (1.5 packets/minute inbound)
- Consequently, slower detection (42mins to dispersion of 30)
- Response time is wrong metric...

False Negatives

- Easy to prove presence, impossible to prove absence
- Live evaluation: over 8 months detected every worm outbreak reported on popular security mailing lists
- Offline evaluation: several traffic traces run against both Earlybird and Snort IDS (w/all worm-related signatures)
  - Worms not detected by Snort, but detected by Earlybird
  - The converse never true
False Positives

- **Common protocol headers**
  - Mainly HTTP and SMTP headers
  - Distributed (P2P) system protocol headers
  - Procedural whitelist
  - Small number of popular protocols
- **Non-worm epidemic Activity**
  - SPAM
  - BitTorrent

Limitations/ongoing work

- Variant content
  - Polymorphism, metamorphism
  - Newsom et al., *Polygraph: Automatically Generating Signatures for Polymorphic Worms*, Oakland ’05
- Network evasion
  - Normalization at high-speed tricky
- End-to-end encryption vs content-based security
  - Privacy vs security policy
- Self-tuning thresholds
- Slow/stealthy worms
- DoS via manipulation

Summary

- Internet-connected hosts are highly vulnerable to worm outbreaks
  - Millions of hosts can be "taken" before anyone realizes
  - If only 10,000 hosts are targeted, no one may notice
- Prevention is a critical element, but there will always be outbreaks
- Containment requires fully automated response
- Scaling issues favor network-based defenses
- Different detection strategies, monitoring approaches
  - Very active research community
- Content sifting: automatically sifting bad traffic from good