CSE 454

Security III
“Outbreak!”

Internet Outbreaks: Epidemiology and Defenses

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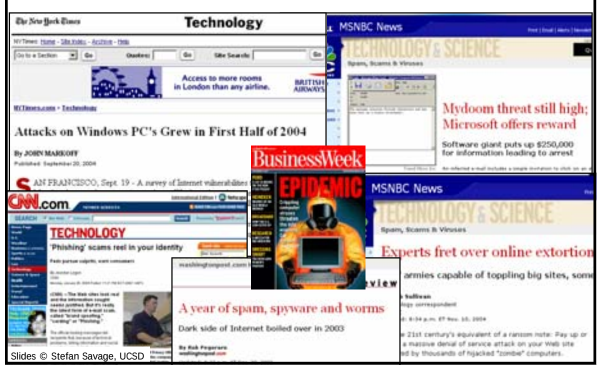
Collaborative Center for Internet Epidemiology and Defenses (CCIED)

- **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…



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

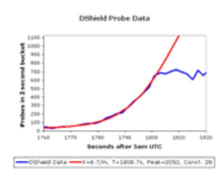
- No longer just for fun, but for profit
  - SPAM forwarding (MyDoom.A backdoor, SoBig), Credit Card theft (Korgo), DDoS extortion, etc…
  - Symbiotic relationship: worms, bots, SPAM, etc
  - Fluid third-party exchange market (**millions** of hosts for sale)
    - Going rate for SPAM proxying 3 -10 cents/host/week
    - 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

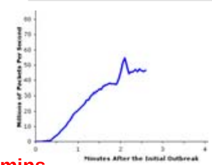
Today's focus: Outbreaks

- 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)

A pretty fast outbreak: Slammer (2003)

- 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
  - **>55million IP scans/sec**
- **90% of Internet scanned in <10mins**
  - Infected ~100k hosts (conservative)

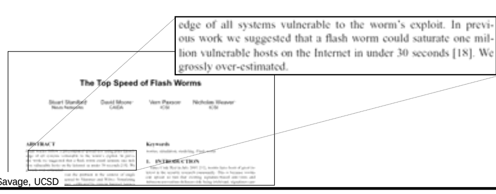




See: Moore et al, IEEE Security & Privacy, 1(4), 2003 for more details

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!

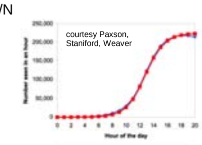


How to think about worms

- 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
  - ß: contact rate
  - i(t): I(t)/N, s(t): S(t)/N

$$\frac{dI}{dt} = \beta \frac{IS}{N} \qquad \frac{dS}{dt} = -\beta \frac{IS}{N} \quad \rightarrow \quad \frac{di}{dt} = \beta i (1-i)$$

$$i(t) = \frac{e^{\beta(t-T)}}{1+e^{\beta(t-T)}}$$



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 2005 (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, hitlist, topological,…)
  - Vulnerability distribution (e.g. density – S(0)/N)
- How **frequently** are infections attempted?
  - ß: 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 ß 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
  - Rescorla, *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

proactive

- Automated patch creation: fix the vulnerability on-line
  - Sidiroglou et al, *Building a Reactive Immune System for Software Services*, USENIX '05
- Anti-worms: block the vulnerability and propagate
  - Castaneda et al, *Worm vs WORM: Preliminary Study of an Active counter-Attack Mechanism*, WORM '04

reactive

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 ß 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

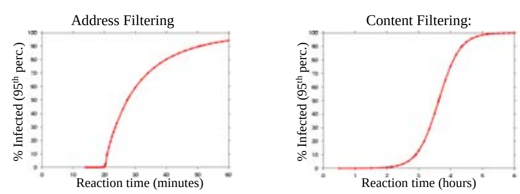
- **Simulate spread of worm across Internet topology**
  - Infected hosts *attempt* to spread at a fixed rate (probes/sec)
  - Target selection is uniformly random over IPv4 space
- **Source data**
  - Vulnerable hosts: 359,000 IP addresses of CodeRed v2 *victims*
  - Internet topology: AS routing topology 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

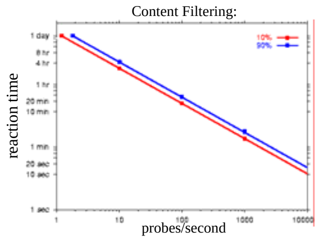
- Assume **every host** employs the containment strategy
- Two containment strategies :
  - ***Address filtering:***
    - Block traffic from malicious source IP addresses
    - Reaction time is relative to each infected host
    - **MUCH** easier to implement
  - ***Content filtering:***
    - Block 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?

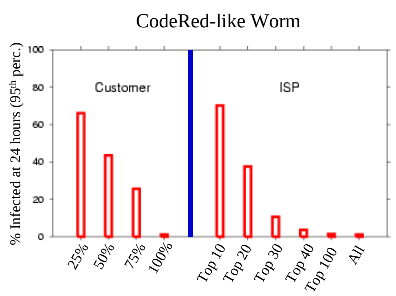


- Reaction times must be fast when probe rates get high:
  - **10 probes/sec: reaction time must be < 3 hours**
  - **1000 probes/sec: reaction time must be < 2 minutes**

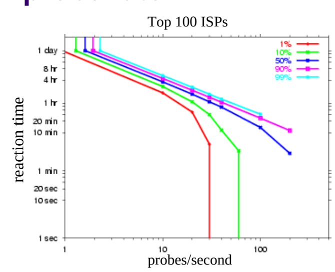
Limited network deployment

- 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.

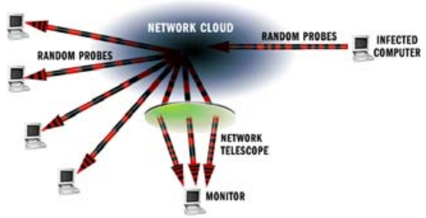
Defense requirements summary

- **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? Lets 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

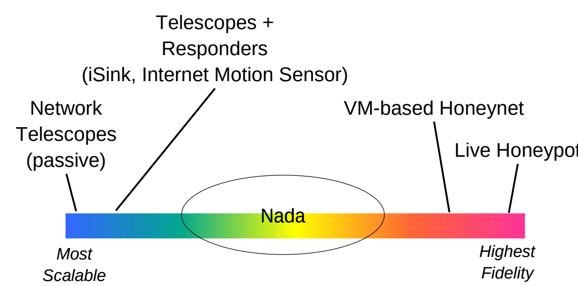
Telescopes + Active Responders

- 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

HoneyNets

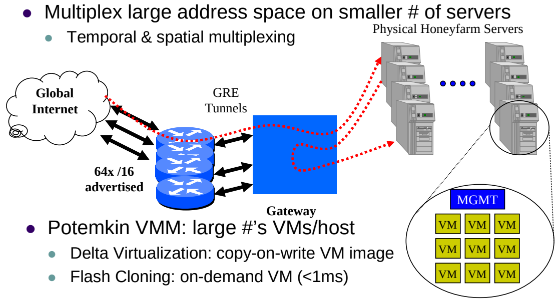
- Problem: don't know what worm/virus would do? No code ever executes after all.
- Solution: redirect scans to real "infectable" hosts (honeypots)
  - Individual hosts or VM-based: Collapsar, HoneyStat, Symantec
  - Can reduce false positives/negatives with host-analysis (e.g. TaintCheck, Vigilante,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

The Scalability/Fidelity tradeoff



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



- Potemkin VMM: large #'s VMs/host
  - Delta Virtualization: copy-on-write VM image
  - Flash Cloning: on-demand VM (<1ms)

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

Scan Detection

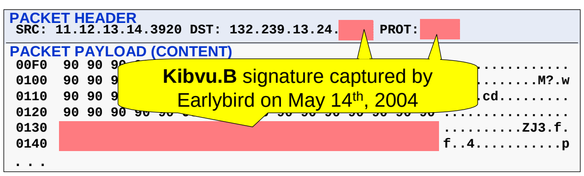
- Idea: detect worm's infection attempts
  - In the small: ZoneAlarm, but how to do in the network?
- Indirect scan detection
  - Wong et al, *A Study of Mass-mailing Worms*, WORM '04
  - Whyte et al. *DNS-based Detection of Scanning Worms in an Enterprise Network,* NDSS '05
- Direct scan detection
  - 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

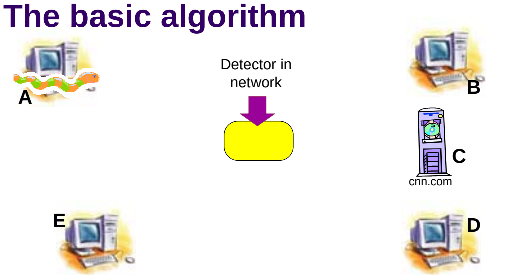
- Monitor network and look for strings common to traffic with worm-like behavior
- Signatures can then be used for content filtering



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

The basic algorithm

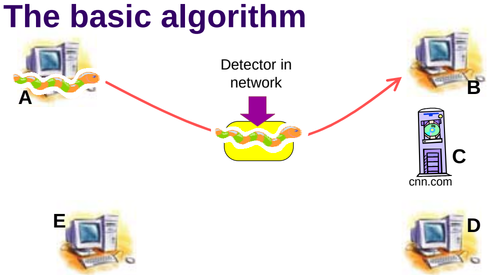


Prevalence Table

Address **Dispersion** Table

Sources	Destinations

The basic algorithm



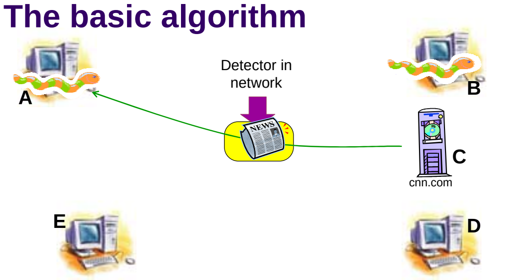
Prevalence Table

(worm)	**1**

Address **Dispersion** Table

Sources	Destinations
1 (A)	**1 (B)**

The basic algorithm



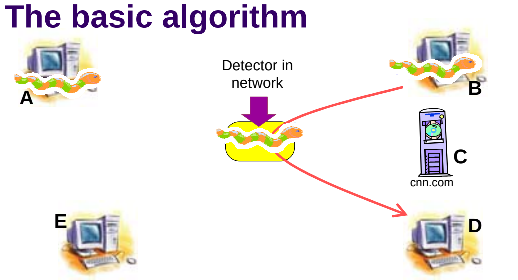
Prevalence Table

	1
	1

Address **Dispersion** Table

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

The basic algorithm



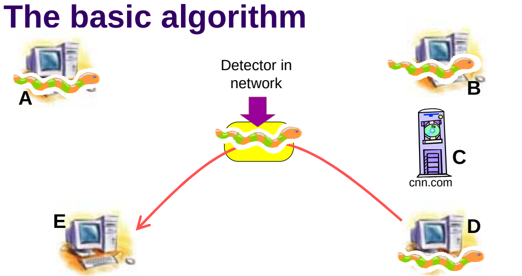
Prevalence Table

	2
	1

Address **Dispersion** Table

Sources	Destinations
2 (A,B)	2 (B,D)
1 (C)	1 (A)

The basic algorithm



Prevalence Table

	3
	1

Address **Dispersion** Table

Sources	Destinations
3 (A,B,D)	3 (B,D,E)
1 (C)	1 (A)

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

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)
- Alternatives? More efficient algorithms.

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 A B C D O M

Fingerprint = 11000000

P2 R A B C D 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

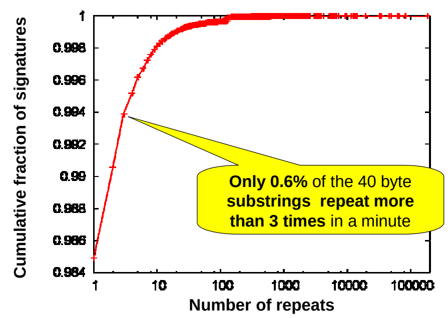
A B C D E F G H I J K

Fingerprint = ...000000

SAMPLE IGNORE IGNORE SAMPLE

- P_{track} → 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_{track} = 99.64% for a 400 byte invariant**

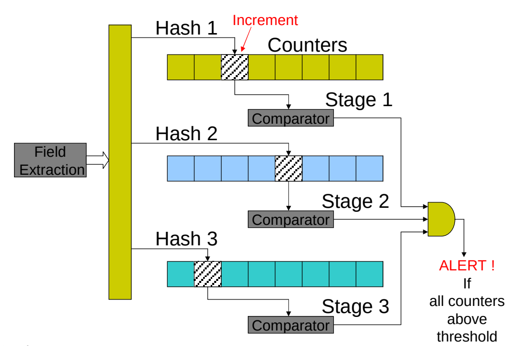
Observation: High-prevalence strings are rare



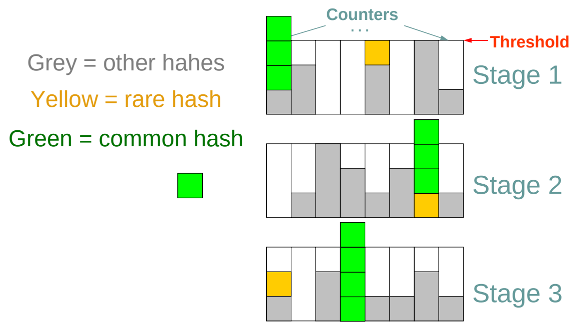
Efficient high-pass filters for content

- 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



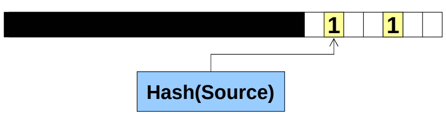
Multistage filters in action



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

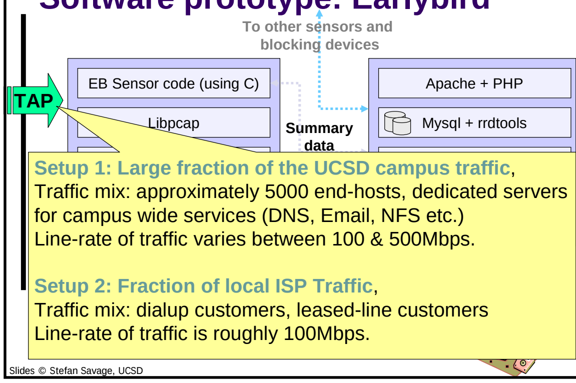
$$\text{Error Factor} = 2/(2^{numBitmaps}-1)$$

- With 3, 32-bit bitmaps, error factor = 28.5%

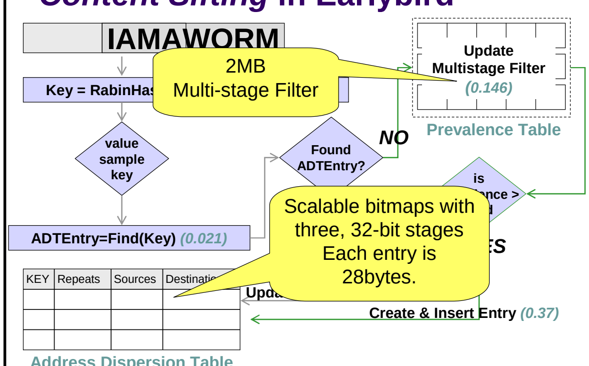
Content sifting summary

- 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



Content Sifting in Earlybird



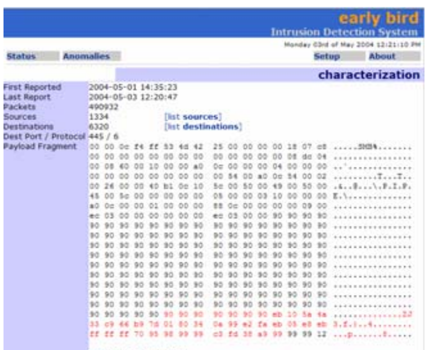
Content sifting overhead

- 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**

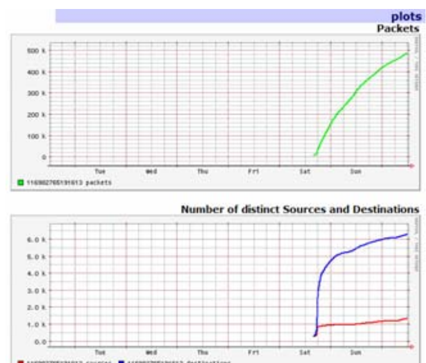
Experience

- 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

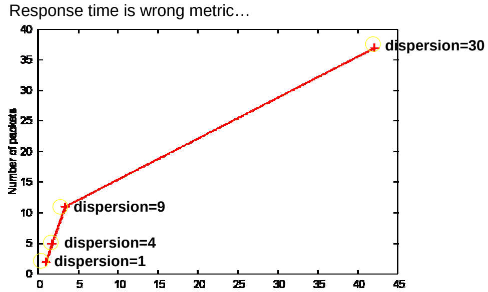


Sasser



Kibvu

- 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

```
GNUTELLA.CONNECT
/0.6..X-Max-TTL:
.3..X-Dynamic-Qu
erying:.0.1..X-V
ersion:.4.0.4..X
-Query-Routing:.
0.1..User-Agent:
.LimeWire/4.0.6.
.Vendor-Message:
.0.1..X-Ultrapee
r-Query-Routing:
```


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 sift bad traffic from good