Exploiting Underlying Structure for Detailed Reconstruction of an Internet-scale Event

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Proc. ACM Internet Measurement Conference 2005

Enhancing Telescope Imagery

NGC6543: Chandra X-ray Observatory Center (http://chandra.harvard.edu)
Enhancing Telescope Imagery

The “Witty” Worm

- Exploited flaw in the *passive analysis* of Internet Security Systems products
- Worm fit in a *single* Internet packet
  - *Stateless*: When scanning, worm could “fire and forget”
- Vulnerable pop. (12K) attained in 75 minutes.
- Payload: *slowly corrupt random disk blocks.*
- Flaw had been announced the *previous day.*
- Written by a Pro.
What Exactly Does Witty Do?

1. Seed the PRNG using system uptime.
2. Send 20,000 copies of self to randomly selected destinations.
3. Open physical disk chosen randomly between 0 .. 7.
4. If success:
   5. Overwrite a randomly chosen block on this disk.
7. Else:

Witty Telescope Data

- UCSD telescope recorded every Witty packet seen on /8 ($2^{24}$ addresses).
  - But with unknown losses

- In the best case, we see $\approx 4$ of every 1,000 packets sent by each Witty infectee.

? What can we figure out about the worm?
Generating (Pseudo-)Random Numbers

• *Linear Congruential Generator* (LCG) proposed by Lehmer, 1948:
  \[ X_{i+1} = X_i \cdot A + B \mod M \]

• Picking A, B takes care, e.g.:
  \[ A = 214,013 \]
  \[ B = 2,531,011 \]
  \[ M = 2^{32} \]

• Theorem: the *orbit* generated by these is a complete permutation of 0 .. 2^{32}-1

• Another theorem: we can invert this generator

```c
srand(seed) { X ← seed }
rand() { X ← X*214013 + 2531011; return X }

main()
1. srand(get_tick_count());
2. for(i=0;i<20,000;i++)
3.   dest_ip ← rand()[0..15] || rand()[0..15]
4.   dest_port ← rand()[0..15]
5.   packetsize ← 768 + rand()[0..8]
6.   packetcontents ← top-of-stack
7.   sendto()
8. if(open_physical_disk(rand()[13..15] ))
9.   write(rand()[0..14] || 0x4e20)
10. goto 1
11. else goto 2
```
What Can We Do Seeing Just 4 Packets Per Thousand?

- Each packet contains bits from 4 consecutive PRNGs:
  3. \( \text{dest\_ip} \leftarrow \text{rand}()_{[0..15]} \| \text{rand}()_{[0..15]} \)
  4. \( \text{dest\_port} \leftarrow \text{rand}()_{[0..15]} \)
  5. \( \text{packetsize} \leftarrow 768 + \text{rand}()_{[0..8]} \)
- If first call to \( \text{rand}() \) returns \( X_i \):
  3. \( \text{dest\_ip} \leftarrow (X_i)_{[0..15]} \| (X_{i+1})_{[0..15]} \)
  4. \( \text{dest\_port} \leftarrow (X_{i+2})_{[0..15]} \)
- Given top 16 bits of \( X_i \), now brute force all possible lower 16 bits to find which yield consistent top 16 bits for \( X_{i+1} \) & \( X_{i+2} \)

\[ \Rightarrow \text{Single} \] Witty packet suffices to extract infectee’s complete PRNG state! Think of this as a sequence number.

Cool, But So What?

- E.g., Individual Access Bandwidth Estimation
  - Suppose two consecutively-observed packets from source \( S \) arrive with states \( X_i \) and \( X_j \)
  - Compute \( j-i \) by counting # of cranks forward from \( X_i \) to reach \( X_j \)
  - # packets sent between the two observed = \( (j-i)/4 \)
  - \( \text{sendto} \) call in Windows is blocking
  - Ergo, access bandwidth of that infectee should be \( (j-i)/4 \times \text{size-of-those-packets} / \Delta T \)
  - Note: works even in the presence of very heavy packet loss
Inferred Access Bandwidth of Individual Witty Infectees

Precise Bandwidth Estimation vs. Rates Measured by Telescope
Systematic Telescope Loss

Telescope Comparison
Telescope Bias

<table>
<thead>
<tr>
<th>CAIDA &gt; Wisc.*1.05</th>
<th>Wisc. &gt; CAIDA*1.05</th>
</tr>
</thead>
<tbody>
<tr>
<td># Domains</td>
<td>TLD</td>
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</tr>
<tr>
<td>3</td>
<td>.gov</td>
</tr>
<tr>
<td>25</td>
<td>other</td>
</tr>
</tbody>
</table>

`srand(seed) { X ← seed }
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4 calls to rand() per loop
Plus one more every 20,000 packets, if disk open fails ...
... Or complete reseeding if not
Witty Infectee Reseeding Events

• For packets with state $X_i$ and $X_j$:
  – If from the same batch of 20,000 then
    • $j - i = 0 \mod 4$
  – If from separate but adjacent batches, for which Witty did not reseed, then
    • $j - i = 1 \mod 4$
      (but which of the 100s/1000s of intervening packets marked the phase shift?)
  – If from batches across which Witty reseeded, then no apparent relationship.
Permutation Space

$X_0$  $X_{2^{32}}$

20,000 packets  20,000 packets

Seed  Failed Disk Write

Permutation Space

$X_0$  $X_{2^{32}}$

$4x$  $4y$  $4z+1$

Pkt  Pkt  Pkt  Pkt
We Know Intervals in Which Each *First-Seed* Packet Occurs ....

• … but which among the 1,000s of candidates are the actual seeds?
• Entropy isn’t all that easy to come by …
• Consider
  \[
  \text{srand(get\_tick\_count())}
  \]
  i.e., uptime in msec
• The values used in repeated calls increase linearly with time
Slope = 1000/sec
Time back to X-intercept = uptime
Uptime of 750 Witty Infectees

Uptime of 750 Witty Infectees
Given Exact Values of Seeds Used for Reseeding …

• … we know exact random # used at each subsequent disk-wipe test:
  
  \[
  \text{if(open\_physical\_disk(rand()_{13..15})}
  \]
  
• … and its success, or failure, i.e., number of drives attached to each infectee …

Disk Drives Per Witty Infectee

![Diagram showing percentage of infectees with different numbers of drives]

- % Infectees w/ # Drives
Given Exact Values of Seeds Used for Reseeding …

• … we know exact random # used at each subsequent disk-wipe test:
  \[
  \text{if(open\_physical\_disk(\text{rand}(), n_{13..15})}
  \]
• … and its success, or failure, i.e., number of drives attached to each infectee …
• … and, more, generally, every packet each infectee sent
  – Can compare this to when new infectees show up
  – i.e. Who-Infected-Whom
Time Between Scan by Known Infectee and New Source Arrival At Telescope

Infection Attempts That Were Too Early, Too Late, or Just Right
Witty is Incomplete

- Recall that LCD PRNG generates a complete orbit over a permutation of 0..2^{32}-1.
- **But**: Witty author didn’t use all 32 bits of single PRNG value
  - \( dest_{\text{ip}} \leftarrow (X_i)_{[0..15]} \| (X_{i+1})_{[0..15]} \)
  - Knuth recommends top bits as having better pseudo-random properties
- **But**\(^2\): This does *not* generate a complete orbit!
  - Misses 10% of the address space
  - Visits 10% of the addresses (exactly) twice
- So, were 10% of the potential infectees protected?

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Time When Infectees Seen At Telescope

![Diagram showing time when infectees seen at telescope and their infection rate.](image)
How Can an Unscanned Infectee Become Infected?

- Multihomed host infected via another address
  - Might show up with normal speed, but not *early*
- DHCP or NAT aliasing
  - Would show up *late*, certainly not *early*

- Could they have been *passively infected* extra quickly because they had large cross-sections?
- Just what are those hosts, anyway?

Uptime of 750 Witty Infectees

*Part of a group of 135 infectees from same /16*
Time When Infectees Seen At Telescope

Analysis of the Extra-Quick Hosts

- Initial infectees exhibit super-exponential growth ⇒ they weren’t found by random scanning
- Hosts in prevalent /16 numbered x.y.z.4 in consecutive /24 subnets
- “Lineage” analysis reveals that these subnets not sufficiently visited at onset to account for infection
- One possibility: they monitored networks separate from their own subnet
- But: if so, strange to number each .4 in adjacent subnets …

⇒ Unlikely infection was due to passive monitoring …
Alternative:
Witty Started With A “Hit List”

• ...Unlikely infection was due to passive monitoring ...

• Prevalent /16 = U.S. military base
• Attacker knew of ISS security software installation at military site ⇒ ISS insider (or ex-insider)
• Fits with very rapid development of worm after public vulnerability disclosure

Are All The Worms In Fact Executing Witty?

• Answer: No.
• There is one “infectee” that probes addresses not on the orbit.
• Each probe contains Witty contagion, but lacks randomized payload size.
• Shows up very near beginning of trace.
⇒ Patient Zero - machine attacker used to launch Witty. (Really, Patient Negative One.)
  • European retail ISP.
  • Information passed along to Law Enforcement.
Summary of Witty Telescope Forensics

- Understanding a measurement's underlying structure adds enormous analytic power
- Cuts both ways: makes *anonymization* much harder than one would think
- With enough effort, worm “attribution” can be possible
  - But a *lot* of work
  - And no guarantee of success

VAST Architecture
Clearing House Architecture

Remote Sites

- Clearing House
- Clearing House
- Clearing House

Communication Platform

Operator

Local Site

Clearing House

Analysis Logic (e.g., extended Bro)

Site Information

- Apache
- Bro
- Windows
- SSH