

Corrupted DNS Resolution Paths: The Rise of a Malicious Resolution Authority

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Abstract

We study and document an important development in how attackers are using Internet resources: the creation of malicious DNS resolution paths. In this growing form of attack, victims are forced to use rogue DNS servers for all resolution. To document the rise of this “second secret authority” on the Internet, we studied instances of aberrant DNS resolution on a university campus. We found dozens of viruses that corrupt resolution paths, and noted that hundreds of URLs discovered per week performed drive-by alterations of host DNS settings. We used the rogue servers discovered in this analysis to document numerous live incidents on the university network. To measure this problem on the larger Internet, we generated DNS requests to most of IPv4, using a unique label query for each request. We found 17 million hosts responding, and further tracked the resolution path they used to reach our NS. Unable to find plausible harmless explanations for such a large number of open recursive hosts, we queried 600,000 of these open resolvers for “phishable” domains, such as banks and anti-virus companies. We found that 2.4% of this subsample would reply with incorrect answers, which extrapolates to 291,528 hosts (on the Internet) performing malicious DNS service. With DNS resolution behavior so trivially changed, numerous malware instances in the wild, and so many other hosts providing incorrect and misleading answers, we urge the security community to consider the corruption of the resolution path as an important problem.

1 Introduction

DNS plays an essential and often unquestioned role in the operation of networks. We study and measure a growing malicious behavior whereby individual infected computers are directed to use “rogue” DNS services instead of those provided on their network. This trend differs from traditional DNS attacks, such as poisoning, since it targets individual users instead of servers. Further, since it involves only the victim and a complicit remote server, the attack is difficult to witness outside of the local network.

We document what appears to be the start of a growing form of attack: the subversion of a host’s correct *resolution path*. The client is directed to use a rogue DNS server, which provides incorrect answers to queries or selective manipulation of answers for the purposes of commercial gain, phishing or other abuse. In most cases, the users have no indication that the DNS answers are not what the correct authoritative DNS servers would provide.

The attack is by design difficult to detect outside of the local network. Unlike a phishing site, which security researchers can crawl to find, or a botnet, which researchers can measure through flow logs and honeypots, corrupted path resolution leaves little external evidences. In many networks, users are free to select a DNS recursive server of

their choice, and network administrators lack means to monitor or validate the answers. The open policy with a lack of monitoring stub resolver behavior allows for resolution path corruption to go largely unnoticed.

Our study of local network traffic confirms the presence of a class of infections that force victims to use remote, rogue DNS services. Our study of IPv4 revealed approximately 17 million “open recursive” DNS servers. This alone has remarkable security implications.

To identify hosts that are actively involved in malicious DNS resolutions, as opposed to those merely misconfigured, we sent queries to 600,000 selected hosts, asking them to resolve various bank, anti-virus, search engine, and other “phishable” domains. Even with a random sample of hosts, we found 2.4% provided incorrect or misleading answers, and 2% provided incorrect NXDOMAIN answers (as opposed to SRVFAIL, e.g.). This extrapolates to a population of approximately 291,528 hosts on the Internet that potentially provide incorrect or malicious answers.

These two observations must be read together in context: there are numerous examples of host resolution paths being subverted by malware, and evidence of hundreds of thousands of DNS servers that routinely provide incorrect answers. This pattern, if left unchecked, will lead to the rise of a second, malicious secret resolution authority within the DNS hierarchy. Malware can then trivially change how users experience the Internet: via legitimate recursive servers that correctly surf the DNS zone hierarchy, or via the rogue DNS servers that selectively provide right and wrong answers.

Our paper provides the following contributions: **First:** We define the problem of *DNS resolution path corruption*, and rogue DNS service, as distinct from existing DNS abuses (e.g., cache poisoning, fast flux, etc.). We also note the rise of commercial interests in providing incorrect DNS answers, for the purpose of advertising to customers. **Second:** We describe a technique for measuring the extent to which DNS servers provide malicious or incorrect answers on the wider Internet. **Third:** We note the implications of having the current DNS infrastructure supplanted by a malicious authority service, and suggest measures to defend the resolution path taken by users.

2 Background

We give a brief overview of the Domain Name System (DNS) [Moc87a, Moc87b], a critically-important component of the Internet infrastructure, responsible for mapping names to IP addresses. We focus on those aspects of DNS used for the abuse we study. For a general and readable overview of DNS, see [Vix07].

2.1 DNS Operation

DNS is a distributed database that uses a tree structure to organize a namespace, composed of labeled nodes (the root is an empty label). A domain is a node, and fully qualified domains are the bottom-up concatenation of nodes, which each label separated by a period.

A *zone* is a clique of nodes, which form a contiguous tree structure, the top of which is called the *start of authority*, or SOA. The SOA delegates naming authority downward, to *delegation points*, or else terminates with *leaf nodes*. The contents of the SOA are available from authority servers, which typically transmit data to recursive servers, which in turn provide general resolution services for local users. Recursive servers that allow anyone on the Internet to use them for name resolution are informally called *open recursive*. Such servers are actually one of a set of open resolvers:

1. *Open Recursive* resolvers provide open access to a *full resolver*.
2. *Open Recursive/Forwarding* or *Open Forwarding* resolvers proxy access to a full resolver.
3. *Open Caching servers* have recursion disabled, but still provide access to cached entries.
4. *Restricted Resolvers* provide access to authoritative data.

Each node in a zone contains *resource records* (or RR sets) that contain, typically, mappings between host names and IP addresses. Each RR has a shelf life, or TTL (time to live), measured in seconds, which begins to decay when it is sent from the authority server to caching servers.

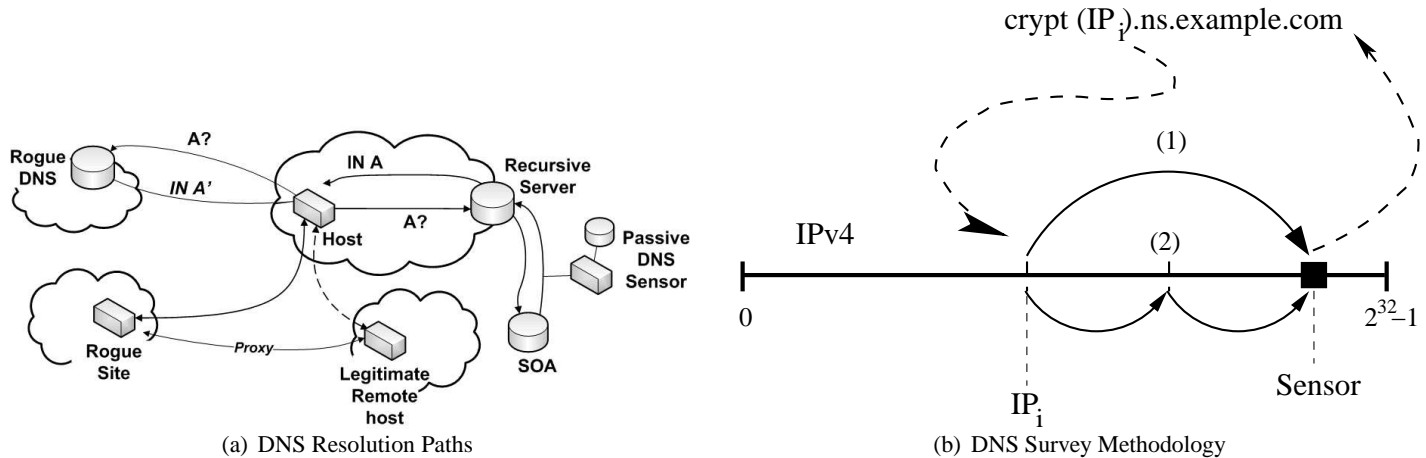


Figure 1. a) Conceptual view of normal and corrupted DNS resolution paths, indicated as $IN A$ and $IN A'$ answers respectively. Passive DNS monitoring is also indicated. (b) DNS Survey methodology, revealing host resolution behavior as either (1) open recursive or (2) recursive forwarding.

DNS clients are varied and many. Typically, operating systems and applications provide limited resolver libraries. Their lack of caches, and typical inability to climb the zone hierarchy to locate records, earn these libraries the name “stub resolvers”. Stub code uses the recursive services specified by the host operating system, which is typically set by an administrator, or acquired during a dynamic address allocation session. The recursive resolver used by the stub libraries, together with the upstream zone access behavior of the full resolver, constitutes a *resolution path*.

Significantly, most operating systems permit sufficiently privileged users to change the default resolution behavior of stub libraries. And some applications, such as browsers, have their own stub resolvers, which may allow each user to change or proxy resolution behavior.

2.2 DNS Poisoning and Resolution Path Corruption

Since DNS (as opposed to DNSSEC) lacks robust authentication mechanisms, the resolution path taken by a computer is critical to how it experiences the Internet. Typically, whatever answer is provided by a recursive server is implicitly taken as correct by the stub resolver. The lack of authentication, and ability to spoof UDP-based DNS, gave rise to a series of DNS poisoning exploits, e.g., [Bel95, AA04, Sym04], wherein malicious answers were forged and relayed to recursive servers.

Attacks against stub resolvers are typically not called DNS poisoning, since stubs often lack caching. Usually attacks on stub resolvers involve altering the recursive path used by the host to process all resolution requests. I.e., instead of poisoning a cache line in a DNS server, an attack on a stub resolver points the host to a malicious, rogue DNS server.

Figure 1(a) shows a conceptual view of how resolution paths can be subverted for malicious purposes. Users normally request the address of a desired host by consulting a full resolver, such as their network-provided recursive server. The recursive server surfs the zone hierarchy to locate the desired resources, here simplified in Figure 1(a) as a connection to an authority server. A subverted resolution path will cause the infected host to instead use a different resolver, which returns incorrect answers (indicated as $IN A'$ in Figure 1(a)). The user is then sent to a rogue site, which may optionally proxy the connection to the original, legitimate site, or perform other deceptions (e.g., phishing).

A few malware samples have altered the DNS resolution path, as shown in Figure 1(a). The *ghost* trojan, for example, altered host DNS settings and browser proxy settings in 2003 [Sop03]. A more recent family of trojans called the *DNSChanger*, did this in only a few lines of code.

Perhaps the most famous example of malware changing host resolution behavior was the `zcodec` trojan of 2006. `ZCodec` enticed users to install a “free video player” or codec. In reality, the trojan altered the host “NameServer” registry key, which takes precedence over all DHCP-assigned DNS resolution paths, and directed users to rogue DNS servers. [EZ06]. According to web popularity ranking services, the site used to distribute the `zcodec` trojan briefly rose to within the top 15,000 pages on the entire Internet, over a 3-year average of rankings [Ale07]. The site is still active today.

In this paper, we investigate the degree to which the subversion of resolvers has occurred. Changing a user’s resolution path by redirecting her to a malicious DNS server requires the malicious DNS server to be *open recursive*. As such, we are also presenting data from an Internet-wide survey on the prevalence of open recursive servers.

3 Study Methodology

As noted in Section 2, abuses in DNS path resolution are difficult to measure outside of the local network. Since victims contact remote servers directly, the only opportunities to observe the attack are (1) on the compromised host, (2) at the complicit DNS server, or (3) at the local network. We view the first two as difficult and unlikely sampling points, respectively. Observing malicious DNS behavior at the local network level has difficulties as well. Local operators may observe DNS queries leaving their network, destined for remote machines, but absent a policy restricting the use of DNS, they lack direct means of determining whether the traffic they observe is correct.

We therefore measured this problem from both ends: by studying resolution patterns in a local network, and by attempting to find suspicious resolution paths on the Internet at large. For the former, we tapped DNS traffic at a campus border. For the latter, we performed a comprehensive survey of all of IPv4, using a technique that forced open resolvers to contact our nameservers.

By working in both directions, we found evidence of malicious DNS usage on the local network, and found convincing but indirect evidence of this phenomena on the larger Internet.

The following sections describe these two approaches in details.

3.1 Local Network Observation

We captured two months of DNS traffic at a busy campus gateway and parsed the packets for the query and resource records. The traffic tap reflected the resolution behavior of approximately 18,000 users. We used a setup similar to Passive DNS Replication [Wei05]. Passive DNS focuses on answer streams directed at resolvers. However, corrupted DNS paths do not transit through local resolvers, and instead make direct connections to rogue DNS servers. We therefore tapped all egress DNS traffic, both UDP and TCP by a simple port filter.¹

During the two month capture period, 390 GB of network trace files of DNS-only traffic with a total of one billion resource records from 4.5 billion packets. (Since our sample period also overlapped with our DNS probe study, discussed below in Section 3.2, many queries went to non-open resolvers, and were never answered.)

3.2 Internet-Wide Resolution Survey

We also want to measure what we observed in our local network on the Internet at large. This is a difficult problem, since the remote, complicit DNS server potentially controls the entire resolution path. That is, we would not have an opportunity to witness some malicious resolutions at the root, TLD or authority levels, since the rogue DNS server may not even consult the zone hierarchy to find the correct answer. Indeed, in many cases the rogue servers provided incorrect answers.

Without the cooperation of numerous network operators, it would be impossible to *directly* measure the extent to which malicious DNS traffic transits on the Internet. We reasoned, however, that since an attacker might not know the

¹Special care was made to protect the privacy of the students and anyone wishing to reproduce this study would be well-advised to consult their network operators for guidelines

IP address of his victim beforehand, the malicious DNS resolver is therefore very likely to act as an open recursive server. That is, they must accept all queries from potential victims, since there is no straightforward way to determine who will ultimately fall prey to a virus.

This reasoning leads us to search for open resolvers, and then identify those that are likely providing malicious DNS services. Our general approach was to pose recursive DNS queries to all of IPv4, for labels that we uniquely controlled.

We started by organizing IPv4 into a series of classful addresses, and excluded non-routable addresses, e.g., [IAN02], using the bogons list published by Team Cymru [Tea07]. We further excluded CIDRs allocated to the U.S. Military and U.S. government. We obtained these addresses by consulting routing prefixes announced by US-government owned ASNs.² The remaining addresses were randomly shuffled, and the ordering of the addresses preserved. This allowed the survey to be stopped and restarted as needed.

For each address, we calculated a label using a hexadecimal representation of a blowfish encryption of each IP. Thus, to a given IP address, IP_i , we asked for an A-record for:

blowfish(IP_i).parentzone.example.com

For the parent zone of the hashed label (called *parentzone* in the example above), we used a zone that we controlled, and had delegated NS authority. In other words, we asked a unique query to each of the hosts, about a host in our delegated zone. This ensured two properties were maintained in each query. First, each query to each IP would be unique, and therefore (a) not cached by any intermediate server, (b) not easily guessable, even though we did not anticipate problems with spoofed answers in this round of study, and (c) trivially reversible given the blowfish key, so that one can efficiently find which of the billions of IP addresses corresponds to a given label. Second, we ensured that recursive resolutions would be sent to our NS, allowing us to see what resolution path was taken by the hosts.

We used a specialized responder that would answer any well-formed A? record query with the IP addresses of the resolver that queried the responder. By answering with the IP address of the host that asked for an authoritative resolution, this provided another mechanism to correlate the IP address of the open resolver.

Figure 1(b) shows a conceptual view of how we performed the resolution. Our desire was to not merely enumerate which hosts performed open resolutions, but also find *how* each host looked upward in the zone tree. Figure 1(b) shows two conceptual paths for resolution by the resolver: either (1) directly querying our NS for the A-record, or (2) forwarding the request to another recursive server. We imagined that the first path might correspond to, for example, a misconfigured nameserver that was also open recursive. The second path represents an open forwarder, as discussed in Section 2, such as a home computer that forwarded DNS requests to the ISP's DNS servers, and then provides the answer supplied by its recursive resolver.

The other two types of open resolvers, open cache and authoritative, were not relevant, and so we did not design a probe technique to map them specifically. Open cache resolvers, for example, do not provide recursion, and authority servers only return records for their zone. That is, of the four types of open resolvers noted in Section 2, only the first two were deemed to be useful in an DNS path corruption attack.

We performed two studies of IPv4. In our second scan of IPv4, once we determined that an IP address functioned as an open-recursive resolver, we performed additional queries to fingerprint the implementation of the DNS server. The three additional queries we sent were a query for `version.bind` in the CHAOS name space, a truncated query where we set the TC bit and an IQUERY that is a deprecated way of performing a reverse lookup.

We created fingerprints for each resolver from the response packets according to Bernstein's methodology [Ber02], which consists of concatenating the codes described in Appendix A, Table 2 depending on fields and flags in the DNS response.

In addition to the DNS queries, we also performed an HTTP GET request against the IP address of the open resolver to determine if it was also running an HTTP server. A successful GET request allowed us to analyze the HTTP headers for information such as a the Server version and the timezone the server ran in. We pretended to be a version of Internet Explorer as some Storm bots return more interesting payloads for that user agent, see [GVN⁺07].

²Based on previous experiences with DNS surveys, we found that sending DNS queries to these networks invariably resulted in questions forwarded to our campus network abuse group. We reasoned that such carefully watched networks were unlikely to have open resolvers.

4 Analysis

Our study focuses on a class of attack that changes the resolution path of hosts, and directs users to malicious DNS servers. Although some anti-virus vendors report in depth on this problem, (see the analysis in [Cor07, HL07]), we wanted to find local evidence of resolution path corruption. We then applied our DNS scan technique to see if we could find evidence of this abuse in the wider Internet.

4.1 Evidence of Local DNS Abuse

The data collected at the university core router was enormous. In [ZBW07], the authors were able to use hand analysis and simple threshold analysis to spot several common trends. For example, they sorted alphabetically the domain query strings, and easily found typo squatting domains. Likewise, they sorted domains by the number of A-records to find fast flux [The07] behavior. We observed these behaviors as well, but our task required us to find much smaller needles in the haystack.

We used two approaches to locate path corruption examples. First, we matched queries against the open recursive DNS servers and Storm infected nodes. That is, if university users were sending queries to remote open recursives or known bots, we could use this as a low pass filter, and further analyze the matching traffic. Second, we also obtained and ran DNS altering malware and monitor the IP addresses it uses for DNS. We then used the IPs of the rogue DNS servers to bootstrap the search for infected hosts.

To identify malware samples that change DNS settings, we took 194,372 virus execution traces from the Malfease project, <https://malfease.oarci.net>, and examined the underlying execution trace, which includes system calls, to see if the malware altered windows registry keys affecting DNS resolution. We found 6 samples that changes the “NameServer” registry key. We further performed a search on Malfease for malware identified by AV tool scans as affecting DNS, e.g., the Trojan.DNSChanger virus. While hardly complete, since this depends on the non-standard naming conventions of vendors, it helped characterize the samples.

There were too few PE32 binary samples that changed the DNS path to reveal any trends. So we consulted the malware detection infrastructure used by Google [PMM⁺07], and looked for web pages that, when visited, would cause hosts to change their DNS resolution settings (e.g., by using web exploits to alter the host NameServer registry key). Over the last six months, we found 2107 such pages distributed over 605 domains. In total, these pages pointed hosts to 75 unique remote DNS servers. The graph in Figure 2(a) shows the number of URLs encountered weekly is quite high. Our data suggests that this form of attack is a current and prevalent threat.

The trend we observe is that, after the initial DNS-altering virus in 2003, numerous virus samples started to appear in 2005 that changes host resolution paths, e.g., DNSCharger. These viruses-driven changes were supplemented or replaced with web-based exploits that performed the same. This attack exposes the victim to identity theft, without the need for elaborate host-based keylogging or rootkits. All of the malicious behavior exists on remote servers, made all the more agile by the use of a rouge DNS server.

We executed 8 samples of DNS changing malware in honeypots, and observed the changes made to the honeypot’s resolution settings. This yielded a set of 8 different IP addresses pointed to by the viruses. We reasoned that traffic to/from those IPs would be most likely malicious, and used this as a filter for our trace files. We checked our DNS data collection, and found numerous instances of DNS traffic sent to remote sites from the campus network. In several cases, a remote DNS server in Russia served as the primary recursive DNS server for several compromised machines on the US-based university network.

Due to the massive number of packets and IPs collected, a bloom filter [Blo70, BM05] was employed to find the overlap of DNS replies coming into the campus from known malicious hosts. The bloom filter was constructed with 2^{26} slots ($67108864\text{bits} = 8$ megabytes) and three hash functions. The input set of DNS resolvers was 1.6 million IPs, and we needed to intersect this with upwards of 17 million open recursive IPs. This yields a $\frac{m}{n}$ ratio of approximately 42, and with $k = 3$ our false positive ratio equaling $\left(1 - \left(1 - \frac{1}{m}\right)^{kn}\right)^k = 0.000368$ or 0.0368%. We hand verified the results to remove any false positives.

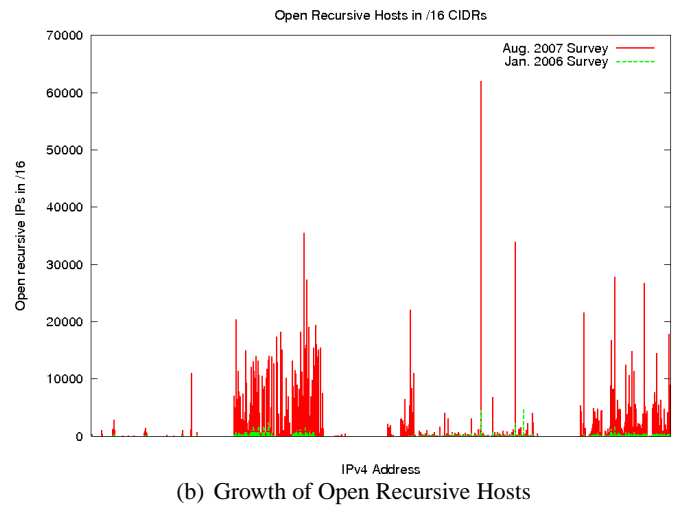
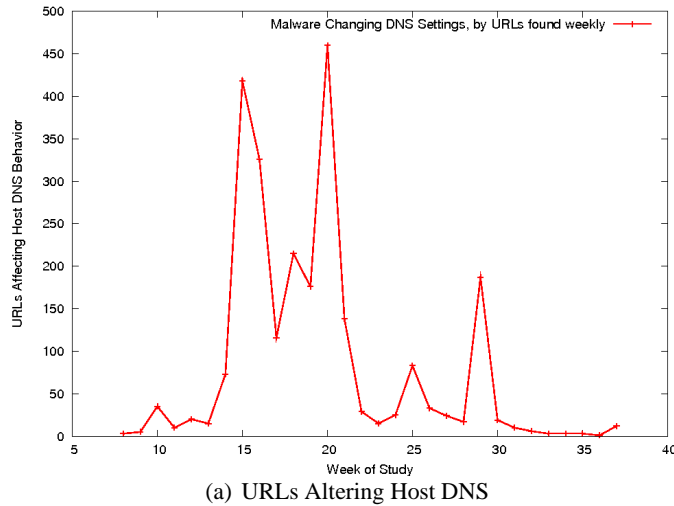


Figure 2. (a) URLs encountered per week that alter host DNS settings. (b) Prevalence of Open Recursion in IPv4 /16s, January 2006 and August 2007 compared.

By performing this overlap analysis, we were able to quickly find several infected hosts on campus. In these cases, the hosts were using remote open recursive servers and their DNS resolution path had been maliciously changed. Specifically, there were several instances of campus hosts using known malicious resolvers from the Ukraine region for queries like `time.windows.com`, `www.amazon.com`, `www.facebook.com`, and `sb.google.com`. The queries were blocked from reaching the servers, so we did not learn what answers were provided. Below, we describe how we generated queries to other, non-blocked rogue DNS servers, and documented incorrect answers.

4.2 Understanding the Nature of Open Recursives

Despite the relatively small numbers of malware samples that altered DNS settings, we nonetheless found numerous infected individuals in an average-sized university. This suggests there may be a wider prevalence. While our evidence of local malicious DNS traffic caused by infections was quite clear, finding a similar pattern of abuse on the wider Internet is not as straight forward. As noted in Section 2 it is nearly impossible to directly observe. Our recursive probe technique, however, gave us a starting point for indirect evidence.

Our general analytical approach was to take the set of open recursive servers, and attempt to find which ones were used for malicious DNS services. We applied a series of filters (e.g., removing linux hosts, and embedded DSL devices), in order to better locate malicious resolvers.

Our late August 2007 scan found 10,427,588 open resolvers, while our early September 2007 scan found 10,573,140 resolving hosts. The union of the two sets yields 17,365,759 open resolvers, since only 3,634,969 IPs were in common. The scans were only a few weeks apart, suggesting a mass migration of some 7 million DNS server addresses.

The August and September numbers were also a significant increases over a January 2006 scan that found only 634,941 hosts. To illustrate the IP diversity gained by this increase, a plot of the January and August data appears in Figure 2(b), where IP address is plotted on the x-axis, and counts of open resolvers by /16s form the y-axis. The high points in graph represent space allocated to ISPs.

We note that according to site ranking services, the `zcodec` malware propagation site reached its peak popularity (a top 15,000 site) in Q3 of 2006—months after our initial survey. By looking at the reports of the gross numbers of open resolvers found by others (e.g., [Wes07], who reported a spike in open recursive hosts in July, 2007), we theorize

that just in the last year, there has been a dramatic rise in the number of open resolvers in only the last year, on the order of several million.

This by itself has profound implications for security, given the role these machines could play in denial of service attacks using DNS amplification [US-06]. Clearly not all open resolvers provide malicious DNS services. With tens of millions of open recursive hosts observed, we endeavored to find harmless explanations for the open recursive behavior in our data.

We first theorized that some of these open recursive hosts could be hobbyist machines or open source DNS servers used by small businesses. Linux machines could of course have their resolution paths changed, but we found it unlikely the `win PE32`-based binaries corrupting host resolution act on unix machines outside of specialized emulation contexts.

To test this explanation, we analyzed the pattern of resolutions used by hosts. When performing recursive lookups, linux hosts generate a distinct pattern of AAAA queries, followed by an A query, because of the forward IPv6 compatibility logic in `glibc, glibc-2.6.1/resolv/gethnamaddr.c`. That is, linux hosts perform an IPv6 lookup (regardless of whether there's a non-link-local v6 interface), and then an IPv4 lookup when the query fails or the querying host has no 6-stack. As a result, when we observed a host performing the resolution pattern (AAAA then A) to our NS, we deemed it to be a linux host. This heuristic will have diminished value when Vista's stub resolver is refined.

We found that only 169,407 of the open recursive hosts used one of 37,429 unique linux forwarding resolvers. Filtering our list of open recursives this way did not provide a satisfying explanation for the large number of resolvers. There had to be other factors behind these open recursive hosts.

We next theorized that many of the open recursive hosts were running a DNS server embedded in a home networking appliance, such as a premium DSL router. Since we also sent a web request to open resolvers, we checked for hosts answering with server strings that correspond to embedded devices (e.g., RomPager, Agranat-EmWeb). Here, the theory was that these embedded devices, while perhaps poisonable using traditional DNS cache attacks, were less likely to be used as a resolving authority for malicious purposes. A break down of the server strings appears in Table 7. We found a total of 417,327 such hosts—again too few to explain the surge in open recursive servers.

We next looked at properties of the recursive servers themselves, and how they resolved our probes. As noted in Section 3, we tracked the IP address of the open recursive resolver that we asked to resolve a query and the IP address that eventually contacted our authoritative name server for that query. We recorded approximately 23 million such pairings. About 96.4% or about 15 million resolvers forwarded their query to another resolver. Whereas only about 580,000 resolvers contacted our name server directly. We analyzed the number of IP addresses and /24s behind each forwarding resolver. Approximately 71% of forwarded resolvers have only one open recursive resolver that forwards to them and 87% of all resolvers have only a single /24 that forwards to them, and shown in Figure 3.

Some resolvers received recursive forwards from over 20,000 different /24s. The resolvers with a large number of forwards from open recursive servers are mostly located in China, Korea and the USA (Table 4b). The network and geographic diversity found in these IPs was curious, since it was not clear what the relationship existed between so many open resolvers, and other hosts in remote countries and networks. The actual recursive forwards with the most clients using them are located in Italy, Netherlands, and the United States. The top 10 recursive forwarding servers are listed in Appendix Table 3. We found that a high percentage of hosts using a particular forwarder are in the same country as the forwarder.

Although, approximately half of the legitimate DNS servers are configured correctly to be not open-recursive, the forwarding tables we have built allow us to query even closed resolvers. Any open-recursive server that forwards its queries to the closed resolver can be used to query the closed DNS server. Although, there is a chance that the open-recursive might be lying, we can probe many of them and then do a majority vote on the answers.

We continued to look for explanations about the behavior of these open recursive servers. So we next compared them with two different sets of known recursive resolvers. The first set was a subsample of DNS servers resolving Google domain names, totaling some 900,000 IPs over a period of three months. Essentially, this was a sampling of IPs that consulted the authority servers for `google.com`—DNS servers refreshing cache entries. The other set consisted of about 80,000 IP addresses contained in the “glue records” for the `.com` TLD. Essentially, these were the IP addresses

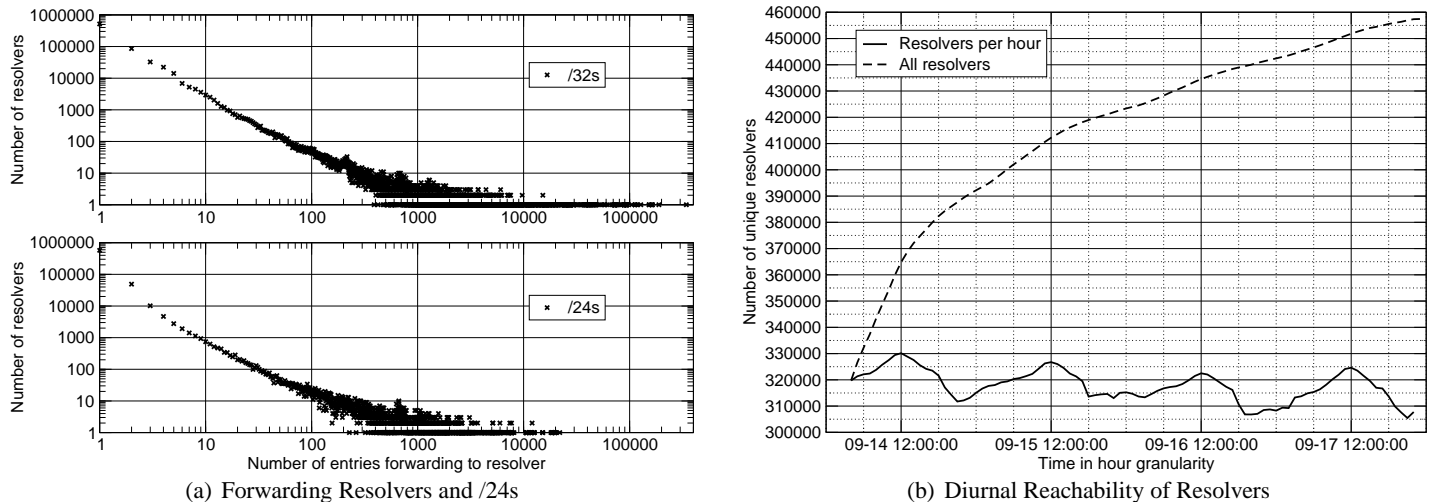


Figure 3. (a) the number of resolvers being used to resolve forwarded query and how many open recursive IP addresses or /24 networks are forwarding to them. The distribution follows Zipf’s law. (b) A diurnal pattern of hosts probed over time, suggesting home users acting as resolvers.

of nameservers listed in the .com zone.

Since these hosts were already known to be DNS servers, we sought to explain what fraction of the 17 million open recursive servers were observed to be DNS servers in other contexts. We found about 50% of the glue IP addresses in our set of open recursives and about 25% of the Google resolvers. The overlapped hosts are likely DNS servers, misconfigured to be open recursive. There remained, however, a very large number of open recursive hosts, numbering in the millions, whose role as a DNS server cannot be explained. The fact that they did *not* consult the authority servers for google.com suggests they forward recursive queries to other machines.

Unable to find other plausible harmless explanations, we instead began to look for *negative* explanations of the hosts behavior. We consulted the “BL history” of each IP. We built a database of every black listed host noted by SpamHaus [Spa07], for a period of six months prior to our study. We used SpamHaus’s “XBL”, or exploits block list as a reference for IP reputation, since this notes IP addresses that are know to hosting or sending malware (e.g., viral attachments in email). Hosts are delisted automatically after a few weeks, or by request.

Figure 4 shows the distribution of 396,000 open resolvers in our study that had a negative BL history. Many had short listings—often a single event, while others had persistent, mutli-week listing times. This is fairly typical of dynamic hosts that SpamHaus tracks. We similarly noted the overlap between our open resolvers and the Storm-infected hosts. We obtained a list of Storm bots, using a variety of data sources. [Thr07, GVN⁺07]. We counted 754,159 hosts in the Storm botnet that were open recursive.

5 DNS Servers That Lie

Thus far, our analysis generated a set of open resolvers, and noted (a) the remarkable migration of 7 million hosts between scan events, (b) the lack of any satisfying explanation for why these hosts are otherwise open resolvers (e.g., authority servers, embedded devices, linux machines). To find the hosts in this set that were being used for malicious resolution purposes, we designed a second study.

We selected a set of approximately 600,000 resolvers that were chosen from three different categories: 200,000 selected uniformly random from all 17,000,000 resolvers, 200,000 selected from resolvers that overlap with resolvers contacting Google, and 200,000 IP addresses selected from known Storm bot infected nodes. Over a period of four

Country/Type	Number of resolvers	Answering	All True	All Lies	NXDomain	Buggy
All	593092	457643 (77.2%)	446689 (97.6%)	566 (0.1%)	9955 (2%)	212 (0%)
Storm	211778	166869 (78.8%)	164107 (98.3%)	86 (0.1%)	2560 (2%)	26 (0%)
Google	192629	160385 (83.3%)	158129 (98.6%)	105 (0.1%)	1829 (1%)	142 (0%)
Random	188685	130389 (69.1%)	124453 (95.4%)	375 (0.3%)	5566 (4%)	44 (0%)
Other Fingerprints	319684	227007 (71.0%)	220143 (97.0%)	422 (0.2%)	6244 (3%)	90 (0%)
Fingerprint: 1q1	141490	123747 (87.5%)	122052 (98.6%)	70 (0.1%)	1482 (1%)	102 (0%)
Fingerprint: ttt	107049	89795 (83.9%)	87484 (97.4%)	72 (0.1%)	2149 (2%)	20 (0%)
Fingerprint: 5q5q	24869	17094 (68.7%)	17010 (99.5%)	2 (0.0%)	80 (0%)	0 (0%)
Unknown OS	553956	423212 (76.4%)	412443 (97.5%)	556 (0.1%)	9796 (2%)	207 (0%)
RomPager	31260	26733 (85.5%)	26572 (99.4%)	4 (0.0%)	149 (1%)	3 (0%)
Linux	7876	7698 (97.7%)	7674 (99.7%)	6 (0.1%)	10 (0%)	2 (0%)
USA	127008	101851 (80.2%)	97196 (95.4%)	293 (0.3%)	4327 (4%)	11 (0%)
Turkey	57041	48593 (85.2%)	48581 (100.0%)	1 (0.0%)	4 (0%)	7 (0%)
Brazil	30900	24876 (80.5%)	24850 (99.9%)	5 (0.0%)	13 (0%)	2 (0%)
Spain	30458	21867 (71.8%)	20070 (91.8%)	2 (0.0%)	1794 (8%)	0 (0%)
Japan	21370	16758 (78.4%)	16737 (99.9%)	4 (0.0%)	13 (0%)	0 (0%)
India	17611	16094 (91.4%)	16054 (99.8%)	1 (0.0%)	20 (0%)	1 (0%)
Peru	16414	15890 (96.8%)	15878 (99.9%)	2 (0.0%)	9 (0%)	1 (0%)
Thailand	15954	14640 (91.8%)	14513 (99.1%)	28 (0.2%)	68 (0%)	6 (0%)
China	28683	13398 (46.7%)	10920 (81.5%)	38 (0.3%)	2406 (18%)	20 (0%)
France	19317	13137 (68.0%)	12893 (98.1%)	9 (0.1%)	236 (2%)	1 (0%)
Italy	16984	12292 (72.4%)	12248 (99.6%)	7 (0.1%)	30 (0%)	0 (0%)
Taiwan	6158	4162 (67.6%)	4004 (96.2%)	12 (0.3%)	15 (0%)	134 (3%)

Table 1. The table shows the geographic distribution of probed resolvers and how they answered to probing queries. The table also shows statistics for the operating system or fingerprint class a resolver belongs to.

days, we asked these IP addresses to resolve 84 different domains. The domains consisted of a subset of banking sites, social networking sites, anti-virus sites and other domains likely to be a subject of Phishing attacks. We sent about 670 probes per seconds so that we would probe each resolver every 15 minutes in average. Over the course of the four days, we sent approximately 220 million probes.

To determine, if a resolver provides incorrect answers, we identified the set of authoritative net blocks that contain valid responses to IN A queries for every single domain. We then compared the answers we received from the probed resolvers and checked if the answers fell within the netblocks we identified. For each probe, we recorded the time it was sent, the answers we received or a timeout in case we did not receive any answers. Figure 3 shows how many unique resolvers answered our probes per hour and also a the cumulative number of resolvers that answered our probes so far. The graphs show that over the course of our study we received answers from approximately 460,000 of the approximately 600,000 resolvers we probed. However, at any given hour, we received answers from only about 310,000 to 330,000 resolvers. In general, we would expect that DNS servers to be available all the time. However, as can be seen in Figure 3, 30% of all answering resolvers are unreachable at any given time. Also, the small diurnal trend we observed seems to indicate that the majority of machines we probed might be end-user devices or hosts that are being turned on and off depending on their usage.

Figure 1 shows statistics for the resolvers organized by country. The country was derived from geo-location data on

the IP address of the resolver. We use four different categories to describe the nature of an open-recursive resolver: `All True` indicates a resolver that answered correctly to all our queries, `All lies` indicates resolvers never correctly answering queries, `NXDomain` indicates resolvers returning addresses to `IN A` queries for non-existent domain names, and `Buggy` for resolvers that return `IN A` records which are off-by-one from the correct answer in one of the octets of an IP address.

A resolver that never correctly answers a query is often indicative of captive portals where users need to authenticate before they can use the Internet. Making these resolvers accessible over the Internet is likely due to incorrectly configured devices. It is interesting to note that Turkey has the largest fraction of resolvers that return accurate answers. The country with the largest fraction of resolvers answering for non-existent domains is China.

In addition to looking at the geographic distribution of resolvers, we also analyzed them according to the sample set they belonged to: Random, Storm or Google. There are no significant differences but for the fact that the randomly sampled set has a larger fraction of resolvers that answer for non-existent domains.

We also separated the resolvers into different classes depending on their DNS fingerprint and the operating system implied by the HTTP Server header. We notice that resolvers running Linux web servers have much higher availability and more correct query answers compared to the set of resolvers for which we could not determine an operating system version.

To understand the user experience of a compromised DNS resolution path victim, we visited the pages returned as the answer to our queries for regular websites like Ebay, Amazon, and Google. We captured each of these pages into a database and extract them later for analysis. By hand analyzing over 250 randomly sampled webpages, we found the common types of misdirection and built heuristics to detect them. A large number of sites were parked domain splash pages (although the real domain does exist) with 221 pages for one domain, 224 pages for another, and 96 for yet another. We also found 48 proxied google pages, 29 Chinese splash sites, and 66 Comcast pages requesting a completion of registration. All of these pages, of course, could be altered trivially by the proxying host. And all of them let the remote site act as a man-in-the-middle for all transactions (checking mail, logging in, searching etc.)

5.1 Commercial Abuse of DNS

Companies such as Nominum, Paxfire, Barefruit, Simplicita, and OpenDNS derive commercial value from altering some DNS answers. The primary motivation is a practice informally called *error-path correction* in which bad user input errors lead to DNS queries that should normally return `NXDOMAIN`. Instead of forwarding `NXDOMAIN` to the end host, the DNS resolver returns `IN A` records to an IP address that returns advertisements and search results relating to the incorrectly entered host name. In some cases, the commercial resolvers also return incorrect `IN A` records when a DNS query has timed out. In the case of OpenDNS, the user is prevented from resolving known malicious (phishing) domains. This practice is the dual opposite of the involuntary, malicious path corruption attacks noted in Section 4.

Our analysis shows that approximately 2% of all resolvers answer for non-existent domains. This has unfortunate consequences for non-HTTP protocols such as SMTP where mail is being delivered to the `IN A` records if no `IN MX` record can be found. In China, this practice is the most prevalent with about 18% of all probed resolvers answering for queries to non-existent domains.

5.2 Implementation Errors

We found a noticeable number of resolvers that returned incorrect answers due to implementation errors. Although, we have no insights into the nature of the bug, the behavior was deterministic and happened only for queries that return multiple `IN A` records. In some cases, resolvers decremented the second-most-significant octet in one of the `IN A` records, in other cases, we found the least-significant octet decremented. The approximately 200 resolvers we found behaving this way either timed out to our `CHAOS` queries or answered with 9.3.1 or 9.4.1 indicating the version of `Bind` they may have been running.

6 Related Work

The closest work to ours is [ZBW07], which used passive DNS monitoring to observe numerous resolution anomalies such as typo squatting. By sorting epochs of DNS resolutions, and noting the IN A's geographic origins, the authors were also able to identify fast flux domains. Their description of fast flux is more narrow than the HoneyNet Project paper, [The07], which takes a general view of flux, noting that it may involve both DNS indirection via a rotating NS layer, and an HTTP proxy layer. The double-flux described in [The07] is a single example of the misbehavior we describe. Our work considers *resolution path corruption* as a general form of attack, which may involve the use of rotating malicious NS servers, as well as malicious trojans to alter a victim's default recursive behavior, and ultimately, the creation of a second malicious resolution authority.

Part of our analysis of course makes use of passive DNS replication, first introduced by Florian Weimer [Wei05]. Technologically, we merely used a datastore technique similar to Weimer's. From a policy point of view, however, logging DNS traffic *not* flowing to or from known DNS servers, as in [Wei05], has tremendous privacy implications. For this reason, we have not proposed a general extension to passive DNS, and leave this for future work.

Scanning large portions of IPv4 for DNS activity was addressed in [OKM07], where the authors considered how malicious reverse DNS probes can reveal darknet space. Their work endeavored to better mask darknet space, while ours endeavored to discover hosts in routed space.

Our work fits into the larger set of literature that characterizes DNS behavior. In this vein, open recursion has been studied as a security problem on the Internet. [US-06]. Our survey also revealed likely misconfiguration of DNS servers. Our concern was on the intentional malicious subversion of DNS; for a treatment of how general configuration errors affect the robustness of DNS, see [PXL⁺04]

Our survey also noted several DNS deployments that superficially appeared vulnerable. The vulnerabilities of various DNS systems have been observed since [Bel95]. Some portions of our analysis relied in historical information associated with IP addresses, which may have been affected by DHCP churn. In [XYA⁺07], the authors address this issue directly.

7 Conclusion and Future Work

We have witnessed an increase in malware that changes host resolution paths. This trend, combined with a large supply of open recursive hosts, threatens to create a new, malicious second authority within the DNS hierarchy. We urge the attention of the community to the following issues.

Measurement. Our short study provides a glimpse into a group of tens and hundreds of thousands of DNS servers that provide illegitimate services. We need to better understand and detect when this is done for commercial gain, with varying levels of transparency and notification, and when this is done for purely malicious purposes.

DNSSEC/DLV. We believe DNSSEC [Are05a, Are05c, Are05b] provides a solution to malicious path changes (and other issues) provided end-to-end validation is permitted on hosts. It remains to be seen what manipulations malware can have on the host's use of the validation process.

As reported in a recent study [OMZ07], DNSSEC deployment requires good understanding of managing cryptography, e.g., key management, and coordination across administrative domains, and support of gradual roll-out (e.g., supporting the DNSSEC in isolated "islands"). These are non-trivial issues to overcome and will take time before DNSSEC is fully deployed on the Internet. This suggests that DNSSEC Lookaside Validation (DLV) [And06] records may play an important role as well.

Blocking. It seems likely some networks will impose simple restrictions on egress DNS (e.g., as many .aero zones do already) and require the use of local servers. The security community needs to understand how this might create a brittle DNS infrastructure, and what tradeoffs exist in local networks.

Recovery. When rogue DNS servers are taken down or blocked, the victims are left without DNS, and ISPs may face enormous support costs. It is essential that the security community coordinate with the ISPs and law enforcement.

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APPENDIX

t	timeout	RD	RD (Recursion desired) bit set
0	Return code 0: normal answer	AA	AA (Is Authoritative) bit set
1	Return code 1: format error	Z0	Z0 bit set
2	Return code 2: server failure	Z1	Z1 bit set
3	Return code 3: name error	Z2	Z2 bit set
4	Return code 4: not implemented	q	no queries listed in response
5	Return code 5: refused	Q2	two queries listed in response
TC	TC (Message truncated) bit set	D	response included an answer record

Table 2. A list of designations used to fingerprint a DNS response packet.

Country	Forwarder	Open Recursives
Italy	82.53.187.212	316697
Italy	85.38.28.8	215087
Italy	85.38.28.5	178763
Netherlands	213.75.17.74	157619
Netherlands	213.75.17.76	157513
Netherlands	213.75.76.80	155518
Netherlands	213.75.76.79	155357
Italy	151.99.125.9	144516
Peru	200.48.225.130	123467
Italy	82.53.187.213	116104
USA	71.242.0.36	110472
USA	71.242.0.38	110463
USA	71.242.0.37	110163
Denmark	212.242.34.227	102616

Table 3. The table shows the top 10 recursive forwarding servers and the number of open recursive clients they serve.

Country	Number of forwarded-to resolvers	Percentage	Country	Number of forwarded-to resolvers	Percentage
USA	187990	28.5	China	231	20.1
Japan	58816	8.9	Korea	187	16.3
Germany	51554	7.8	USA	139	12.1
Korea	28595	4.3	Japan	85	7.4
Brazil	26228	4.0	Poland	51	4.4
Taiwan	25886	3.9	Germany	47	4.1
China	24672	3.7	Spain	46	4.0
Russia	21620	3.3	France	46	4.0
Great Britain	21409	3.2	Turkey	38	3.3
France	20819	3.2			
Canada	16935	2.6			
Poland	14654	2.2			
Netherlands	13823	2.1			
Italy	9369	1.4			

(a) Location of all resolvers that are being used as forwards from open recursive resolvers.

(b) Location of resolvers that get forwards from more than 1,000 different /24s.

Table 4. The table shows the location of forwarded-to resolvers and how many sub resolvers are forwarding to them.

Count	Percent	Query	Iquery	TC	Chaos
2694403	(26.3%)	ORDD	t	t	t
2325179	(22.7%)	ORDD	1q	1	ORDAAD
971579	(9.5%)	ORDD	5q	5q	t
722668	(7.0%)	ORDD	t	t	ORDAAD
403802	(3.9%)	ORDD	5q	5	ORDAAD
333807	(3.3%)	ORDD	t	2	t
291932	(2.8%)	ORDD	t	1	ORDAAD
239063	(2.3%)	ORDD	1q	t	ORDAAD
235423	(2.3%)	ORDD	1q	1	t
214298	(2.1%)	OD	t	t	t
177110	(1.7%)	ORDD	4q	0TCZ2	ORDAAD
175820	(1.7%)	ORDD	5q	5	t
117906	(1.1%)	ORDD	5q	t	t
105578	(1.0%)	ORDD	t	1	t
104396	(1.0%)	ORDD	t	5q	t

Table 5. DNS fingerprints of all open recursive resolvers.

Count	Percent	Query	Iquery	TC	Chaos	Count	Percent	Query	Iquery	TC	Chaos
63820	(39.5%)	ORDD	1q	1	ORDAAD	262003	(31.4%)	ORDD	1q	1	ORDAAD
18852	(11.7%)	ORDD	t	t	t	228765	(27.4%)	ORDD	t	t	t
16761	(10.4%)	OD	t	t	t	55892	(6.7%)	ORDD	t	t	ORDAAD
9773	(6.0%)	ORDD	4q	0TCZ2	ORDAAD	43647	(5.2%)	ORDD	t	1	ORDAAD
7715	(4.8%)	ORDD	t	1	ORDAAD	40598	(4.9%)	ORDD	5q	5q	t
6655	(4.1%)	ORDD	1q	1	t	32144	(3.8%)	ORDD	1q	1	t
6589	(4.1%)	ORDD	1q	t	ORDAAD	26967	(3.2%)	ORDD	1q	t	ORDAAD
3896	(2.4%)	ORDD	t	t	ORDAAD	14844	(1.8%)	ORDD	t	2	t
3891	(2.4%)	ORDD	5q	5q	t	12772	(1.5%)	ORDD	t	1	t
2359	(1.5%)	ORDD	t	1	t	11366	(1.4%)	ORDD	5q	5	ORDAAD
2179	(1.3%)	ORDD	t	0TCZ2	ORDAAD	7371	(0.9%)	OD	t	t	t
1358	(0.8%)	ORDD	1q	t	t	7339	(0.9%)	ORDD	1q	t	t
1306	(0.8%)	ORDD	4q	0TCZ2	t	6439	(0.8%)	ORDD	5q	5q	ORDAAD
						5461	(0.7%)	ORDD	0qD	t	t

(a) DNS fingerprints for resolvers overlapping with Google

(b) DNS fingerprints for resolvers overlapping with Storm/Peacomm

Table 6. DNS fingerprints for resolvers belonging to either Storm or Google.

Count	Percent	HTTP Server Version	Count	Percent	HTTP Server Version	Count	Percent	HTTP Server Version
			76371	(56.1%)	(no answer)	534368	(64.0%)	(no answer)
8132640	(79.3%)	(no answer)	6175	(4.5%)	Microsoft-IIS/6.0	92201	(11.0%)	RomPager/4.07
335827	(3.3%)	RomPager/4.07			Apache/1.3.33	60484	(7.2%)	Nucleus/4.3
205034	(2.0%)	Nucleus/4.3	4273	(3.1%)	Microsoft-IIS/5.0	55624	(6.7%)	mini_httpd/1.19
175488	(1.7%)	Apache/1.3.37	3764	(2.8%)	Apache	33938	(4.1%)	(empty header)
161247	(1.6%)	(empty header)	3351	(2.5%)	Apache/2.2.3	19679	(2.4%)	RomPager/4.51
148699	(1.4%)	Microsoft-IIS/6.0	3211	(2.4%)	Apache/2.0.54	14453	(1.7%)	(no header)
142807	(1.4%)	(no header)	3204	(2.4%)	Apache/1.3.37	5170	(0.6%)	Unknown/0.0
113518	(1.1%)	mini_httpd/1.19	3122	(2.3%)	Apache/2.0.52	3915	(0.5%)	GoAhead-Webs
69517	(0.7%)	GoAhead-Webs	2478	(1.8%)	(no header)	1640	(0.2%)	Microsoft-IIS/6.0
59201	(0.6%)	Microsoft-IIS/5.0	2363	(1.7%)	RomPager/4.07	1300	(0.2%)	nginx/0.5.17
55680	(0.5%)	RomPager/4.51	1944	(1.4%)	Apache/1.3.34	1136	(0.1%)	httpd
53925	(0.5%)	Apache	1727	(1.3%)	Apache/1.3.27	966	(0.1%)	Apache/0.6.5
45083	(0.4%)	Apache/1.3.33	1723	(1.3%)	Apache/2.2.4	843	(0.1%)	ZyXEL-RomPager/3.02
39643	(0.4%)	Apache/2.0.54	1554	(1.1%)	Nucleus/4.3	748	(0.1%)	Apache/1.3.33
34710	(0.3%)	Apache/2.0.52	1229	(0.9%)	Apache/2.0.40	723	(0.1%)	Apache/2.2.3
30806	(0.3%)	Apache/2.2.3	1138	(0.8%)	Apache/2.0.55	653	(0.1%)	Apache/1.3.27
28567	(0.3%)	Apache/1.3.34	964	(0.7%)	Apache/2.0.59	503	(0.1%)	Apache/2.0.54
			912	(0.7%)	Apache/2.0.46	475	(0.1%)	Microsoft-IIS/5.0
			907	(0.7%)	Apache/1.3.26	464	(0.1%)	Apache
			880	(0.6%)	Apache/2.0.53	458	(0.1%)	Apache/2.2.4
(a) HTTP Servers version for all open recursive resolvers			854	(0.6%)				
			(b) Open recursive resolvers overlapping with Google					
						(c) Open recursive resolvers overlapping with Storm		

Table 7. HTTP Servers version of open recursive resolvers.

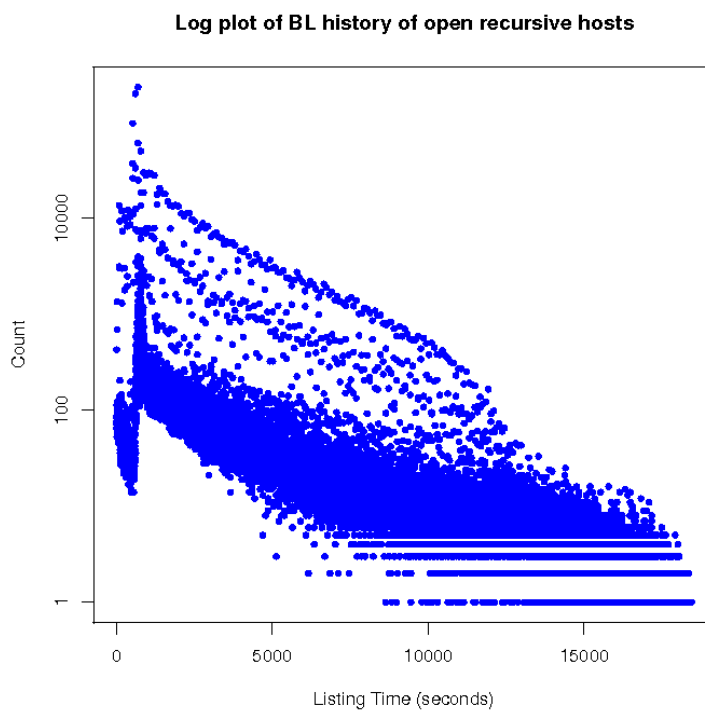


Figure 4. Logscale histogram of time open recursive hosts appeared on virus-related black lists, for 6-month period.