Breaking the links: Exploiting the linker

Tim Brown

June 29, 2011

<mailto:timb@nth-dimension.org.uk>
<http://www.nth-dimension.org.uk/> / <http://www.machine.org.uk/>

Abstract

The recent discussion relating to insecure library loading on the Microsoft Windows platform provoked a significant amount of debate as to whether GNU/Linux and UNIX variants could be vulnerable to similar attacks. Whilst the general consensus of the Slashdot herd appeared to be that this was just another example of Microsoft doing things wrong, I felt this was unfair and responded with a blog post[1] that sought to highlight an example of where POSIX style linkers get things wrong. Based on the feedback I received to that post, I decided to investigate the issue a little further. This paper is an amalgamation of what I learnt. As such it contains my own research, the discoveries of others and POSIX *lore*.

Contents

List of Tables

List of Figures

1 Technical Details

1.1 What is the linker?

The linker is a program that takes one or more objects generated by a compiler and combines them into a single executable program. On GNU/Linux and UNIX variants, linking generally consists of two stages, one during compilation and one at runtime.

1.1.1 The link editor

When a program comprises multiple object files, the link editor (often referred to as `ld`) combines these files into an executable program, resolving the dependencies as it goes along. Link editors can take objects from a collection called a library. Unless a static binary has been requested, link editors do not include the whole library in the output. Rather, they include its symbols (references from the other object files or libraries), as a guide to the runtime linker which will need to be resolved when the binary is executed.

1.1.2 The runtime linker

The runtime linker (generally known as `ld.so`) is actually a special loader that resolves the external dependencies (in the form of symbols) for a given executable prior to execution. It then maps access to the libraries that implement these functions in order to allow successful execution. As we will see below the way the runtime linker functions can vary significantly even between ostensibly similar platforms.

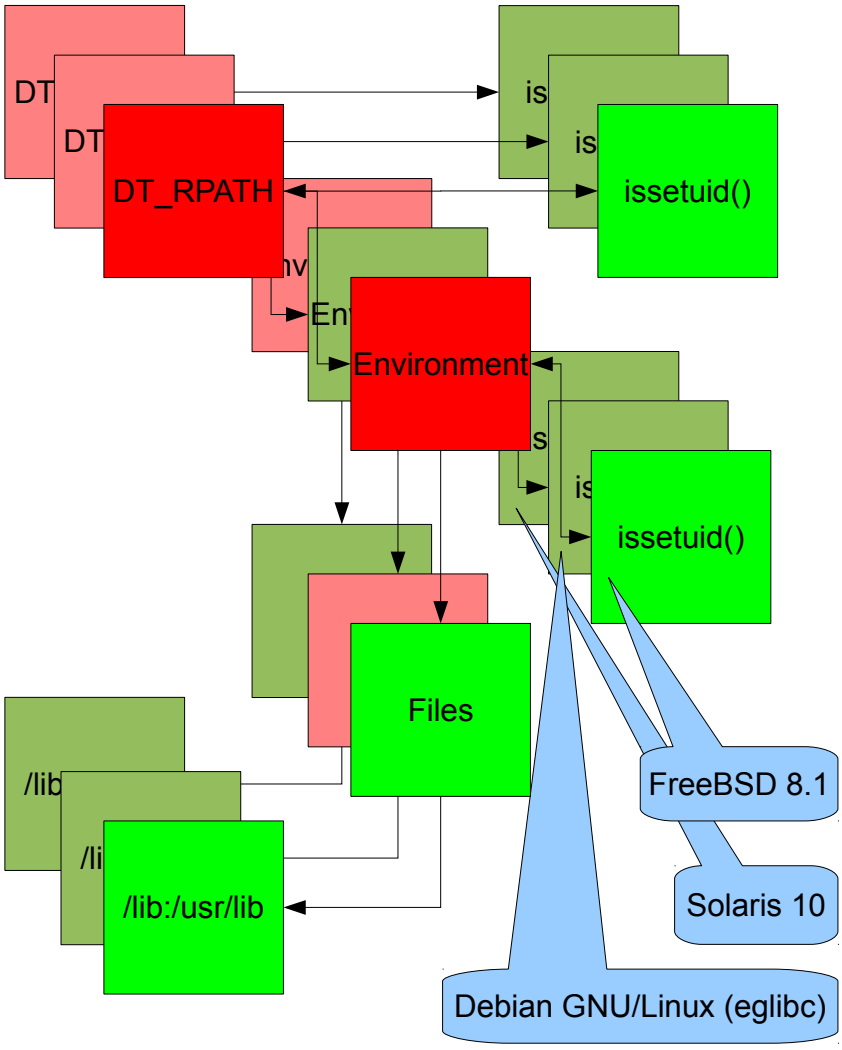
1.2 The linker attack surface

1.2.1 The process of linking and executing

In order to execute a binary, the runtime linker must resolve any dependencies to ensure that externally referenced functions are available within the excecuted binaries process space.
Firstly they look at the hints built into the binary being called. These hints take the form of the `DT_RPATH` and `DT_RUNPATH` ELF headers which consist of colon separated lists of directories that the linker should examine when looking for libraries. The linker will typically check whether the process is setUID or not in order to determine whether macros such as `$ORIGIN` (which points at the binaries own path) should be expanded or not.
In the event that a binary does not have these ELF headers or the linker is unable to resolve all dependencies using the hinted directories, it will then examine environment variables such as `LD_LIBRARY_PATH`. As with the expansion of `$ORIGIN` care should be taken when the process is setUID as if the linker were to trust `LD_LIBRARY_PATH` in such a case then it could be manipulated into loading malicious libraries at the behest of the calling user.
If the linker is still unable to find a dependancy, then the system's default configuration (in the form of the library cache (`ld.so.cache` on Debian GNU/Linux)) is consulted before the linker finally tries the hardcoded directories `/lib` and `/usr/lib`.

In general terms, runtime linkers implement the following flow in resolving dependencies.

Figure 1: Process flow for runtime linker



You'll notice in 1 that certain nodes have been coloured green and red. Whilst I'll explain the reasons for this in more detail later in the paper, nodes that are red contain potential weaknesses that may be exploited by manipulating various facets of the linker attack surface.

1.2.2 Environment

Linkers have a long history of being attacked via environment variables. As you can see below they vary significantly in terms of which environment variables each supports and only a small core of them are present in two or more linkers:

Table 1: Environmental attack surface for Solaris, Debian GNU/Linux and FreeBSD runtime linker

Linker Stage	**Solaris 10**	**Debian GNU/Linux 6.0 (eglibc)**	**FreeBSD 8.1**
ld		LD_RUN_PATH	
ld. so	LD_LIBRARY_PATH[1]	LD_LIBRARY_PATH[1]	LD_LIBRARY_PATH
	LD_PRELOAD[1,7]	LD_PRELOAD[1]	LD_PRELOAD
		LD_TRACE_LOADED_OBJECTS	LD_TRACE_LOADED_OBJECTS
	LD_BIND_NOW[7]	LD_BIND_NOW	LD_BIND_NOW
		LD_BIND_NOT	
		LD_AOUT_LIBRARY_PATH[1]	
		LD_AOUT_PRELOAD[1]	
		LD_NOWARN	
		LD_WARN	
		LD_KEEPDIR	
		LD_ORIGIN_PATH	
		LD_SHOW_AUXV	
		LD_HWCAP_MASK	
		LD_USE_LOAD_BIAS	
		LD_POINTER_GUARD	
		LD_TRACE_PRELINKING	
	LD_DEBUG[1,2,7]	LD_DEBUG[1,2]	
	LD_DEBUG_OUTPUT[2,7]	LD_DEBUG_OUTPUT[1,2]	
		LD_VERBOSE	
	LD_PROFILE[3,7]	LD_PROFILE[1,3]	
	LD_PROFILE_OUTPUT[3,7]	LD_PROFILE_OUTPUT[1,3]	
		LD_ASSUME_KERNEL	
	LD_AUDIT[7]	LD_AUDIT[4]	
	LD_CONFIG[7]		
	LD_DEMANGLE[7]		
	LD_FLAGS[7]		
	LD_LOADFLTR[7]		
	LD_NOAUDIT[7]		
	LD_NOAUXFLTR[7]		
	LD_NOCONFIG[7]		

Continued on next page...

Linker Stage	Solaris 10	Debian GNU/Linux 6.0 (eglibc)	FreeBSD 8.1
	LD_ NODIRCONFIG[7] LD_ NODIRECT[7] LD_ NOENVCONFIG[7] LD_ NOLAZYLOAD[7] LD_ NOOBJALTER[7] LD_ NOVERSION[7] LD_ ORIGIN[7] LD_ SIGNAL[7]		LD_ DUMP_ REL_ POST LD_ DUMP_ REL_ PRE LD_ LIBMAP LD_ LIBMAP_ DISABLE LD_ ELF_ HINTS_ PATH LD_ TRACE_ LOADED_ OBJECTS_ ALL LD_ TRACE_ LOADED_ OBJECTS_ FMT1 LD_ TRACE_ LOADED_ OBJECTS_ FMT2 LD_ TRACE_ LOADED_ OBJECTS_ PROGNAME LD_ UTRACE

Of course there are a whole raft of other variables[2] that can affect the linker but these are the ones supported by `ld` and `ld.so` directly.

1.2.3 Files

In addition to the environment variables listed above, runtime linkers normally have default configurations which they will fall back on when the variables aren't set. The pertinant files are listed below with notes where necessary:

Solaris 10:

- `/var/ld/ld.config`
- `/var/ld/64/ld.config`

  These are typically generated using `crle`.

Debian GNU/Linux 6.0 (eglibc):

[1] Cleared on setUID/SetGID execution

[2] Writes to $0.$$

[3] Writes to /var/tmp/<libraryname> or $LD_PROFILE_OUTPUT/<libraryname> (Solaris) or $LD_PROFILE_OUTPUT (Debian GNU/Linux (eglibc))

[4] Exploited on glibc by Tavis Ormandy: `http://cve.mitre.org/cgi-bin/cvename.cgi?name=CVE-CVE-2010-3847` and `http://cve.mitre.org/cgi-bin/cvename.cgi?name=CVE-2010-3856`

[5] 32-bit versions take the form LD_32_...

[6] Exploited by Nikolaos Rangos (Kingcope): `http://lists.freebsd.org/pipermail/freebsd-announce/2009-December/001289.html`

[7] 32-bit versions take the form ..._32 and 64-bit versions take the form ..._64

- `/etc/ld.so.cache`

  This is typically generated from `/etc/ld.so.conf` and updated when ldconfig is executed, for example as part of the installation of packages.

- `/etc/ld.so.preload`
- `/etc/ld.so.nohwcap`
- `/etc/suid-debug`

  Whilst this isn't documented in the man page for `ld.so` when present it changes how binaries with the setUID bit set are executed.

FreeBSD 8.1:

- `/var/run/ld-elf.so.hints`
- `/var/run/ld-elf32.so.hints`
- `/etc/libmap.conf`
- `/etc/libmap32.conf`

1.2.4 issetugid() and friends

So how does the runtime linker determine whether it should trust user supplied input such the various `LD_...` environment variables. Well it depends, for the most part all runtime linkers examine the real and effective UID of the process, if these are different then the process is considered tainted and user supplied input will be ignored. That's the theory, but in practice it isn't quite that clear cut. Whilst all the linkers I've looked at make this check, it does need to be applied every time the runtime linker considers an environment variable and as Tavis pointed out, it only takes one case where the check is missed before you're in a whole world of pain. Although eglibc does tear down the `LD_...` environment variables, it only does this after it has processed them, so if there's a bug in the `ld.so` this may still be exploitable.
Another factor worth considering is the fact that the GNU/Linux world is moving away from the use of a simple setUID bit on executable to request a change of privileges. In the last month or so, I've started to see discussions on oss-security regarding replacing the setUID bit with file system capabilities[3]. Whilst allowing privilege changes using this mechanism should allow the privileges to be set in a far more granular manner, it will require significant changes to how processes gain and drop privileges, something we're likely to see exploited in due course.

1.3 Real world exploitation

1.3.1 The runtime linker as an interpreter

Imagine a situation in which you've by one means or another managed to get command execution as a non-privileged user and you're looking for a way to elevate your privileges to the root user. You notice that the kernel is unpatched against a known vulnerability but you can't create executable files (for example that pre-compiled version of the exploit you were playing with in your lab last week). This is a real world problem, and one that the runtime linker can help you with. You see, the runtime linker is actually an interpreter, albeit one geared for binaries:

```
user@host:~$ cp /usr/bin/id .
user@host:~$ chmod a-x id
user@host:~$ ls -la id
-rw-r--r-- 1 user user 32176 Oct 30 13:55 id
user@host:~$ ./id
```

```
bash: ./id: Permission denied
user@host:~$ /lib/ld-linux-x86-64.so.2 ./id
uid=1000(user) gid=1000(user) groups=1000(user),20(dialout),24(cdrom),25(floppy),29(audio),
44(video),46(plugdev),50(staff),116(lpadmin)
```

As you can see here, I've taken the `id` binary and removed its execute bits. Whilst it can't be run directly since the execute bits have been removed, the runtime linker (in this case the 64-bit version of eglibc's runtime linker) can still load and execute it without a problem.
So why does this work? Well, taking a look at the permissions on the runtime linker we'll start to see why:

```
lrwxrwxrwx 1 root root 12 Sep 16 12:03 /lib/ld-linux-x86-64.so.2 -> ld-2.11.2.so
-rwxr-xr-x 1 root root 128744 Sep 15 02:31 /lib/ld-2.11.2.so
```

You can see that `ld-2.11.2.so` has execute bits set. The fact is that the runtime linker is just another executable file, albeit one we rarely call directly. Indeed, on most GNU/Linux variants, the `ldd` binary is normally implemented as a shell script wrapper around it:

```
# This is the 'ldd' command, which lists what shared libraries are
# used by given dynamically-linked executables.  It works by invoking the
# run-time dynamic linker as a command and setting the environment
# variable LD_TRACE_LOADED_OBJECTS to a non-empty value.
```

As pointed out by @taviso and @stealth, it's worth highlighting that the Linux kernel's behaviour with regard to `noexec` is different from the norm. Mounting the file system with `noexec` actively prevents the kernel `mmap()`'ing the pages with execute permissions. However from a general hardening perspective, if you're mounting devices with `noexec` then you should also ensure that the runtime linker can't be executed either.

1.3.2 The empty library

So there's been a lot of fuss over the last couple of months about the Microsoft Insecure Library Loading Could Allow Remote Code Execution[4] vulnerability. Whilst it's fair to say that the GNU/Linux dynamic linker doesn't by default include . in its path and you'll very rarely see it listed in `ld.so.conf` and friends, there are some corner cases.
GNU/Linux and POSIX style linkers makes use of a variable called `LD_LIBRARY_PATH` which is consulted when a binary is executed and which takes precedence over the OS default as set in `ld.so.conf`. Consider the following script:

```
#!/bin/sh
export LD_LIBRARY_PATH=$LD_LIBRARY_PATH:/path/to/app/lib
app start
```

What happens if `LD_LIBRARY_PATH` isn't set prior to the script being executed? Well, in that case, the `app` binary is executed with a library path of `:/path/to/app/lib`. This may seem perfectly satisfactory, but here's the rub. When the GNU/Linux dynamic linker sees a path with an empty directory specification such as `:/valid/path`, `/valid/path:` or `/valid::/path`, it treats the empty element as $PWD. This could lead to a library being loaded from the users current working directory which might be exploitable. Go back to the shell script snippet above and consider what would

happen if that was the init script for a privileged process. An administrator needs to stop and start it but he works in a security aware environment and only has access to the init script via the sudo command. So off he goes:

```
user@host:~$ sudo /etc/init.d/app
```

Sudo by default won't change your working directory when it executes a command as another user which means that `LD_LIBRARY_PATH` will end up pointing at the unprivileged user's own directory. What that means is that the GNU/Linux dynamic linker will attempt to load any library dependencies firstly from there.
Since I wrote my blog post highlighting this corner case, a number of real world examples have come to light:

- `http://osvdb.org/show/osvdb/69641` - Mozilla Firefox
- `http://osvdb.org/show/osvdb/70716` - Sun OpenOffice.org
- `http://osvdb.org/search?search%5Bvuln_title%5D=LD_LIBRARY_PATH&search%5Btext_type%5D=alltext` - and many more...

So how can you set `LD_LIBRARY_PATH` safely? Well obviously you can check whether it is set before you append to it, but the following also seems to work quite nicely:

```
export LD_LIBRARY_PATH="${LD_LIBRARY_PATH:+$LD_LIBRARY_PATH:}/path/to/app"
```

It's worth noting too that Debian (at least) are looking to fix[5] the underlying cause.

1.3.3 SIGSEGV'ing for 12 years

Whilst I was fuzzing the various runtime linkers, I came across a number of cases where I could cause my test binary to crash by manipulating the various `LD_...` environment variables. One such case was on Solaris 10 where setting `LD_PRELOAD` as follows:

```
user@host:~$ LD_PRELOAD=: su -
```

leads to a segmentation fault.
The same bug appeared to affect both setUID and normal binaries and yields the following when when the core dump is examined with gdb:

```
Core was generated by `./test'.
Program terminated with signal 11, Segmentation fault.
#0  0xfefcfc71 in ?? ()
(gdb) x/1i $eip
0xfefcfc71:     movsbl (%esi),%ecx
(gdb) info reg esi ecx
esi            0x0      0
ecx            0x0      0
```

which sadly is a NULL pointer dereference inside ld.so.1.
A similar bug was reported publicly[6] in 2005, but according to Sun this one is different. For what it's worth, it's been present since Solaris 8 and affects up to and including the last public release of OpenSolaris.
Sun have assigned issue number 7001523 to this issue.
Further discussions with Sun indicates that this is extremely unlikely to be exploitable since mappings made using mmap() are not preserved during an exec. This rules out the possibility of mapping address zero and then exec()'ing another binary with LD_PRELOAD set.

1.3.4 What's in your RPATH?

I've already spoken in this paper on one such case where the runtime linker can be tricked into using malicious libraries using the LD_LIBRARY_PATH environment variable but there's actually another more interesting case which I'd like to discuss.
If you examine the linker attack surface table above you'll notice that I mention an environment variable LD_RUN_PATH which affects the link editor. By setting this (or indeed the -rpath flag) it is possible to hardset additonal locations where the runtime linker should look when resolving external dependencies. On GNU/Linux at least, when the DT_RPATH or DT_RUNPATH exists within the ELF headers of a binary then these will be honoured first when looking for shared libraries. Additionally, the keyword $ORIGIN within this header is expanded to be the path of the directory where the object is found, while both . and the empty directory specification are honoured, even for binaries with the setUID bit set. From an attackers pespective, setUID binaries with DT_RPATH are particularly nice, since we can make use of hard links to manipulate the runtime linker into using an $ORIGIN which we can control.
By way of a comparison, Solaris and FreeBSD appears to ignore $ORIGIN for setUID binaries and Debian patched the $ORIGIN issues with libc6 2.11.2-7.
Note that Solaris has another problem relating to DT_RPATH which I'll discuss later.
For reference, I took a quick look at three third party applications installed on my test machine, EMC VMware Server, IBM DB2 Express Edition and Oracle XE and found a number of interesting values had been set during the compilation of included binaries DT_RPATH ELF headers.
Firstly let's take a look at Oracle XE. On 10.2.0 I identified that a number of binaries that have DT_RPATH ELF headers that reference $ORIGIN however these aren't generally exploitable as the binaries concerned are likely to be executed from their installed location and since none of the binaries have the setUID flag set. There was however one interesting case where the osdbagrp binary references a fixed, non existent location:

```
host:/usr/lib/oracle/xe/app/oracle/product/10.2.0/server/bin# readelf -d osdbagrp | grep RPATH
0x0000000f (RPATH)                      Library rpath: [/ade/aime1_hrel10/oracle/lib]
```

In the event that an attacker could leverage another bug to create and or write to the /ade/aime1_hrel10/oracle/lib directory or parent then it may be possible subvert the execution flow whenever this binary is called.
Likewise EMC VMware Server 2.0.2 and VMware Workstation 7.1.3 suffers from a similar flaw:

```
host:/usr/local/bin# readelf -d vmrun | grep RPATH
0x000000000000000f (RPATH)              Library rpath: [/build/mts/release/
bora-203138/bora/build/release-x64/apps/vixWrapper]
```

It's worth noting that to perform such an attack would likely require an administrator to be manipulated, both to create the directory with weak permissions and to execute the vulnerable binary.
So we've seen two examples of applications that have minor flaws, how about something useful. Well, as my final example, I looked at IBM DB2 Express Edition 9.7. Like the previous examples

we've seen, DB2 suffers from having binaries that have the `DT_RPATH` set to non-existant directories but in this case there are some other more interesting flaws. Firstly, one of the binaries affected is run by root on system start from `inittab`:

```
host:~# tail -1 /etc/inittab
fmc:2345:respawn:/opt/ibm/db2/V9.7/bin/db2fmcd #DB2 Fault Monitor Coordinator
host:~# readelf -d /opt/ibm/db2/V9.7/bin/db2fmcd | grep RPATH
 0x000000000000000f (RPATH)              Library rpath: [/DoNotCreateThisPath_marker1
.*chglibpath:/opt/ibm/db2/V9.7/lib64:/opt/ibm/db2/V9.7/lib64/N/icc/osslib:
/opt/ibm/db2/V9.7/lib64/C/icc/osslib:/opt/ibm/db2/V9.7/lib64/N/icc/icclib:
/opt/ibm/db2/V9.7/lib64/C/icc/icclib:/
```

But there's more:

```
host:~# readelf -d /opt/ibm/db2/V9.7/bin/db2rspgn | grep RPATH
 0x000000000000000f (RPATH)              Library rpath: [.:/DoNotCreateThisPath_marker1
.*chglibpath:/opt/ibm/db2/V9.7/lib64:/opt/ibm/db2/V9.7/lib64/N/icc/osslib:
/opt/ibm/db2/V9.7/lib64/C/icc/osslib:/opt/ibm/db2/V9.7/lib64/N/icc/icclib:
/opt/ibm/db2/V9.7/lib64/C/icc/icclib:/
```

As you can see, in this case, the value for the `DT_RPATH` ELF header includes `.`, the current working directory which makes exploitation a little easier.
Of course, what we really need is a setUID binary that suffers from such a flaw, and IBM in their wisdom were happy to oblige. Consider the following binary installed as part of IBM Tivoli Monitoring for Databases: DB2 Agent:

```
user@host:~$ ls -la /opt/ibm/db2/V9.7/itma/tmaitm6/lx8266/bin/kbbacf1
-rwsr-xr-x 1 root root 8558 Oct  6 22:11 /opt/ibm/db2/V9.7/itma/tmaitm6/lx8266/bin/kbbacf1
user@host:~$ readelf -d /opt/ibm/db2/V9.7/itma/tmaitm6/lx8266/bin/kbbacf1 | grep RPATH
 0x000000000000000f (RPATH)              Library rpath: [/opt/IBM/ITM/tmaitm6/links/
lnxx86x6-l23-g34/lib:.:./lib:../lib]
```

As you can see, as with the previous case of `db2rspgn`, the value for the `DT_RPATH` ELF header includes `.`, but in this case `kbbacf1` is setUID root. Such a case can be exploited like so:

```
user@host:~$ ./tmb-vs-ibm-db2
PoC exploit for IBM DB2 DT_RPATH privesc.
(c) Tim Brown, 2011
<mailto:timb@nth-dimension.org.uk>
<http://www.nth-dimension.org.uk/> / <http://www.machine.org.uk/>
Constructing bad_libkbb.so...
Have a root shell...
uid=0(root) gid=1000(user) groups=0(root),20(dialout),24(cdrom),25(floppy),27(sudo),29(audio),44(vid
#
```

Oracle has assigned issue number 10319062 to the issue with Oracle XE 10.2.0. Whilst they do not plan to issue a patch (XE is an unsupported product), they have confirmed that the affected binary was not intended to be shipped and will be removing it from future releases. In the case of VMware

Server, EMC's security team confirmed the issue and requested that disclosure was delayed whilst a review of other product lines was performed. Whilst EMC do not intend to issue a patch for VMware Server (again an unsupported product) their review identified that VMware Workstation suffered from the same flaw and in this case a patch will be issued. IBM failed to respond.

1.3.5 Debian makes me sad :(

On Debian GNU/Linux hosts, the runtime linker cache (`ld.so.cache`) is generated from the contents of `/etc/ld.so.conf.d/*` (`/etc/ld.so.conf` just includes the contents of this directory). One of the files included is `/usr/local/lib` which is writable by the `staff` group. This sounds useful but there is a problem. The library search path order generated in the cache is such that dependencies are likely to be resolved *before* the runtime linker gets as far as looking at libraries under `/usr/local/lib`. Because of this I began looking for ways to control the order in which the standard libraries are searched and in doing so I stumbled across the `LD_ASSUME_KERNEL` variable which can be set for the excution of any binary including those that have the setUID bit set. The eglibc man page for `ld.so`[7] states that:

> Every DSO (Dynamic Shared Object, aka shared library) can tell the dynamic linker in glibc which minimum OS ABI version is needed. The information about the minimum OS ABI version is encoded in a ELF note section usually named .note.ABI-tag. This is used to determine which library to load when multiple version of the same library is installed on the system. The `LD_ASSUME_KERNEL` environment variable overrides the kernel version used by the dynamic linker to determine which library to load.

By creating a copy of `libc.so.6` under `/usr/local/lib` with an earlier ABI version and setting the `LD_ASSUME_KERNEL` environment variable to the same version, any user in the `staff` group can cause binaries with the setUID bit set to use our copy like so:

```
user@host:~$ ./test
uid=1000,euid=0,gid=1000,egid=0
user@host:~$ LD_ASSUME_KERNEL=1.1.1 ./test
./test: error while loading shared libraries: libc.so.6: cannot open shared object file:
No such file or directory
user@host:~$ cp libc.so.6 /usr/local/lib/
user@host:~$ LD_ASSUME_KERNEL=1.1.1 ./test
uid=1000,euid=0,gid=1000,egid=0
```

It's worth noting a couple of things about the above attack. Firstly, I had to hexedit the library after compilation to change the change the value of its `.note.ABI-tag` and secondly that after copying `libc.so.6` into `/usr/local/lib`, I had to force `ldconfig` to be executed to update the runtime linker cache. In the real world you'd need to wait for an updated package to call it on your behalf during installation.
Since I orginally wrote this section of the paper, I've been doing some further research and it appears that I actually got this wrong[8], it is not required to set `LD_ASSUME_KERNEL` in order for this to be exploited as the cache generated by `ldconfig` appears to be constructed in reverse alphabetical order and therefore `/usr/local/lib` is checked before `/usr/lib`.

1.3.6 If an environment variables is set but you don't trust it, is it still there?

Having seen how eglibc's runtime linker can be manipulated, there will no doubt be a number of people cracking jokes about long haired hippies so I figured I'd take a look how FreeBSD's runtime linker compares. The FreeBSD man page for `ld.so`[9] seems to indicate that it clears the vast majority of linker related environment variables when it is used to execute but I decided to hook up my fuzzer to make sure it didn't do anything daft.

It seems that whilst it ignores the vast majority of them when resolving runtime dependencies, unlike eglibc used by Debian GNU/Linux, it doesn't actually unset[10] them in `unsetenv` which means they're inheritable by all processes spawned by the setUID binaries. Having a look at the code responsible, it seems to use `issetugid()`[11] to determine whether to trust the environment variables. So far so good right? Well, not exactly, if the setUID binary sets the processes real user ID based on the effective ID. This appears to untaint the running setUID process to a degree where the runtime linker will trust the inherited linker specific environment variables including those such as `LD_PRELOAD` which can be used to modify the execution flow. Further testing appeared to show that the Solaris linker was subject to the same attack.
Whilst I haven't found any cases of setUID binaries that are exploitable in this manner, it does show the difference that subtleties in a linker implementation can make.

1.3.7 Reflections on Trusting Trust revisited

A long time ago, Ken Thompson published a rather interesting paper entitled Reflections on Trusting Trust[12] which discussed the fact that you can't trust code you didn't write yourself (whether you can trust your own code is another matter ;)) in which he discussed the idea of writing a compiler which would introduce vulnerabilities when used to compile arbitrary code. Moreover in his example, it would reintroduce this trojan horse if it detected that it was being used to recompile its own source. He theorised that this could go undetected for a significant amount of time due to peoples inherent trust of the compiler. In the process of writing this paper, I found a great example of such a compiler, although I would like to think that in the case I identified that it wasn't Ken's doing.
The premise of the bug I spotted is such. On Solaris, the `issetugid()` equivalent known as `security()` is used by `ld.so.1` to set a flag on execution (`RT_FL_SECURE`) which the linker later uses to determine whether to trust certain `LD_...` environment variables. Whilst fuzzing the runtime linker, I notice that my test setUID binary appeared to continue to trust certain variables. I was able to call my binary with various `LD_AUDIT` and `LD_PRELOAD` variables and see the referenced libraries load. Corner case 1 was that the referenced library appeared to be loaded if it was in `/usr/lib` and not `/usr/lib/secure` as referenced in Sun's own documentation. The second corner case was that I couldn't reproduce the effect with any of Sun's own setUID binaries just with binaries I compiled myself. Anyway, after much head scratching I realised that `gcc` as distributed by Sun sets a `DT_RPATH` ELF header on every binary it creates, and having dug into the code in some detail that `ld.so.1` will quite happily trust[13] (see `is_path_secure()`) this ELF header even when a setUID binary is being executed. So why does this remind me of Ken's paper? Well, for much of the time I was scratching my head, I hadn't even considered the compiler as the villain of the piece, I'd trusted it to be trustworthy.
So I guess, for most of you the question becomes *is it exploitable*? The answer sadly appears to be no, at least not in most cases. To exploit this bug you need two things to have occurred. Firstly you need a setUID binary compiled using the Sun supplied gcc and secondly you need a library that can be passed via `LD_AUDIT` or `LD_PRELOAD` with a viable constructor or deconstructor. Those of you that are familiar with Tavis's second linker bug will doubtless recognise the second requirement but try as I might I couldn't find any libraries under `/usr/lib` etc that had *useful* functions with this attribute defined, at least not on a default Solaris install.
Sun have assigned issue number 7001536 to this issue and have fixed it in GCC 4.3.2.

1.3.8 Mapping NULL

Strange as it may seem, whilst the GNU/Linux world has finally moved to prevent userland processed from `mmap()`'ing `NULL`, this is not the case on Solaris where it can still be mapped. More strangely still, Sun actually provide a library which maps 0, with the following rationale (taken from the man page for `ld.so.1`[14]:

> The user compatibility library /usr/lib/0@0.so.1 provides a mechanism that establishes a value of 0 at location 0. Some applications exist that erroneously assume a null character pointer should be treated the same as a pointer to a null string. A segmentation violation

occurs in these applications when a null character pointer is accessed. If this library is added to such an application at runtime using LD_PRELOAD, the library provides an environment that is sympathetic to this errant behavior. However, the user compatibility library is intended neither to enable the generation of such applications, nor to endorse this particular programming practice.
In many cases, the presence of /usr/lib/0@0.so.1 is benign, and it can be pre-loaded into programs that do not require it. However, there are exceptions. Some applications, such as the JVM (Java Virtual Machine), require that a segmentation violation be generated from a null pointer access. Applications such as the JVM should not preload /usr/lib/0@0.so—.

1.4 Auditing scripts, binaries and source

1.4.1 Scripts

To check for unsafe concatenation in shell scripts that could lead to empty directory specifications, you can create your own `libc.so` in your home directory and then wait for scripts to fail like so:

```
touch ./libc.so.6 && sudo ...
```

Whilst I'd being playing with privately, it's also fair to mention that @kees_cook also mentioned this approach on Twitter.
Additionally as described in 1.3.2, you can look for constructs such as:

```
export LD_LIBRARY_PATH=$LD_LIBRARY_PATH:/path/to/app/lib
```

1.4.2 Binaries

With binaries you should firstly check the values of any `DT_RPATH` and `DT_RUNPATH` ELF headers within the binaries using one of the following commands:

- `objdump -x ...`
- `readelf -a ...`
- `scanelf` (from PaX)
- `elfdump` (from Sun)

Secondly, as was seen in 1.3.6, you should be wary of any setUID binaries that depend on `setuid()` and which execute further processes without unsetting any inherited environment variables.

1.4.3 Source

Finally, if you're lucky enough to have the source, keep any eye out for the following patterns which will lead to the unsafe ELF headers previously described.
You should look to identify any build scripts, Makefiles or similar which honour the `LD_RUN_PATH` environment variable.
As well as watching out for badly written build scripts you should also look at how gcc and the link editor themselves are called. The following command patters can be problematic.

- `gcc -Wl,-R,...`
- `ld [-rpath`-rpath-link]=...—

- `ld -R ...`

As I've already shown with scripts, the presence of `.` or the empty directory specification of the `DT_RPATH` or `DT_RUNPATH` ELF headers, or in flags being used by `gcc` during the build process could allow libraries to be loaded from the current working directory however you should also be mindful of `$ORIGIN` macros or hard coded directory specications.

1.5 Further research

1.5.1 Other linkers

Through out the process of writing this paper, I've only really looked at 3 platforms, Solaris, FreeBSD and Debian GNU/Linux in any depth. To anyone with an understanding of the UNIX family tree, it should be obvious that there are a number of other POSIX style linkers to explore. Indeed, in the course of writing this paper my attention was drawn to the QNX Neutrino RTOS which RIM are using as the base for their new BlackBerry tablet devices. This has a runtime linker which is capable of loading ELF binaries in which I discovered a flaw which allows the execution flow of setUID binaries to be manipulated.

Some other targets I'd like to examine include:

- Mac OS X
- AIX
- OpenBSD

RIM have assigned PR84526 to the linker flaw in Neutrino.

2 Changes

29th June 2011	Another update with a number of redactions removed
4th January 2011	Updated feedback from Sun/Oracle and EMC. Sun/Oracle okay disclosure of all 3 bugs, EMC confirm VMware Workstation also affected
30th January 2011	Added RIM reference for QNX Neutrino RTOS issue reported on 16th December 2010 and added feedback from Sun on `LD_PRELOAD` bug
5th January 2011	Further bug fixes
16th December 2010	Bug fixes from oss-security
15th December 2010	Initial public presentation at CRESTCon 2010 -, public release of paper on web site and via oss-security mailing list
12th December 2010	Added Sun/Oracle references, Reflections on Trusting Trust revisited, Mapping `NULL` and other misc bug fixes
9th December 2010	Redacted specific vulnerabilities until vendor patches have been released, also added details of linking process
24th November 2010	IBM and EMC contacted regarding DB2 Express Edition and VMware Server
15th November 2010	Sun/Oracle contacted regarding Solaris 10 and Oracle XE
12th November 2010	Incorporated feedback including details on `issetugid()`, `/etc/suid-debug`, file system capabilities, noexec, references and other misc bug fixes. Also added details of `LD_PRELOAD=:` bug
8th November 2010	Initial external peer review, thanks @stealth and @taviso

References

[1] *http://www.nth-dimension.org.uk/blog.php?id=87*

[2] *http://www.scratchbox.org/documentation/general/tutorials/glibcenv.html*

[3] *http://www.openwall.com/lists/oss-security/2010/11/08/3*

[4] *http://www.microsoft.com/technet/security/advisory/2269637.mspx*

[5] *http://www.openwall.com/lists/oss-security/2010/09/29/1*

[6] *http://www.securityfocus.com/archive/1/403575/30/0/threaded*

[7] *http://manpages.ubuntu.com/manpages/lucid/man8/ldo.so.8.html*

[8] *http://bugs.debian.org/cgi-bin/bugreport.cgi?bug=504516*

[9] *http://www.freebsd.org/cgi/man.cgi?query=ld.so*

[10] *http://svn.freebsd.org/viewvc/base/head/lib/libc/stdlib/getenv.c*

[11] *http://svn.freebsd.org/viewvc/base/head/libexec/rtld-elf/rtld.c*

[12] *http://cm.bell-labs.com/who/ken/trust.html*

[13] *http://src.opensolaris.org/source/xref/onnv/onnv-gate/usr/src/cmd/sgs/rtld/common/paths.c*

[14] *http://docs.sun.com/app/docs/doc/819-2239/ld.so.1-1?a=view*