



# A friendly user guide to ELF micropatching with Shiva (alpha v1)

## Shiva Manual

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# 1 Introduction to Shiva

## Shiva is LEJIT!

Shiva is a LEJIT micropatching system for Linux ELF software. LEJIT (Linking & Encoding Just In Time).

## ELF program interpreters

Shiva is an ELF microcode-patching technology that works similarly to the well known (*but little understood*) ELF dynamic linker “/lib/ld-linux.so”. Every ELF program that is dynamically linked has a program header segment type called PT\_INTERP that describes the

path to the *program interpreter*. The program interpreter is a separate ELF program loaded by the kernel that is responsible for helping to build the process runtime image by loading and linking extra modules containing code and data. Traditionally these modules are called shared libraries, and the program interpreter is “/lib/ld-linux.so”. On aarch64 it is “/lib/ld-linux-aarch64.so.1”

Image 1.0: Requesting program interpreter “ld-linux.so”

```
Elf file type is DYN (Shared object file)
Entry point 0x7e0
There are 8 program headers, starting at offset 64

Program Headers:
  Type           Offset             VirtAddr           PhysAddr
   FileSiz        MemSiz              Flags             Align
  PHDR           0x0000000000000040 0x0000000000000040 0x0000000000000040
   0x00000000000001c0 0x00000000000001c0 R               0x8
  INTERP         0x0000000000000200 0x0000000000000200 0x0000000000000200
   0x00000000000001b 0x00000000000001b R               0x1
    [Requesting program interpreter: /lib/ld-linux-aarch64.so.1]
  LOAD           0x0000000000000000 0x0000000000000000 0x0000000000000000
   0x0000000000000a98 0x0000000000000a98 R E            0x10000
  LOAD           0x0000000000000d40 0x0000000000000d40 0x0000000000000d40
   0x00000000000002d0 0x000000000000042e0 RW            0x10000
  DYNAMIC        0x0000000000000d50 0x0000000000000d50 0x0000000000000d50
   0x0000000000000200 0x0000000000000200 RW               0x8
  NOTE           0x000000000000021c 0x000000000000021c 0x000000000000021c
   0x0000000000000044 0x0000000000000044 R                0x4
  GNU_STACK      0x0000000000000000 0x0000000000000000 0x0000000000000000
   0x0000000000000000 0x0000000000000000 RW               0x10
  GNU_RELRO      0x0000000000000d40 0x0000000000000d40 0x0000000000000d40
   0x00000000000002c0 0x00000000000002c0 R                0x1
```

Just like any other interpreter, such as Python, or Java, the ELF program interpreter is responsible for performing various types of loading, patching and transformation.

## Shiva is an ELF program interpreter

Shiva is a newly designed program interpreter who’s sole purpose is to load ELF microcode patches that are written in C and compiled into Shiva modules (ELF relocatable objects). Shiva modules are relocatable objects and by nature already contain the ELF meta-data (*sections, symbols relocations*) necessary to re-build much of the process image. Additionally Shiva has introduced some new concepts such as *Transformations* which are

an extension to traditional ELF relocations, allowing for complex patching operations such as function splicing.

The core purpose of Shiva is to create a microcode patching system that seamlessly fits into the existing ELF ABI toolchain of compilers, linkers, and loaders. Shiva aims to load and link patches that are written 100% in C, in a way that is natural for developers who may not be reverse engineers but are experts in C. Shiva is in-itself a linker and a loader that works alongside and in conjunction with the existing Dynamic linker “ld-linux.so”. To understand more technical details see “shiva\_final\_desing.pdf” within the documentation directory.

## Systems and arch's that Shiva supports

Currently Shiva's AMP tailored-microcode patching system runs on **Linux AArch64**, and supports **AArch64 Linux ELF PIE binaries**. Future support for ARM32, x86\_64/x86\_32 and other requested architectures. At the present moment Shiva doesn't support ET\_EXEC ELF binaries (non-pie) due to time constraints, but it's on the road map.

## 2 Installing Shiva-AArch64

### Download Source code

```
git clone git@github.com:advanced-microcode-patching/shiva
git clone github.com/elfmaster/libelfmaster
```

### Build source code

#### Build and install libelfmaster

Shiva requires a custom libelfmaster branch that has not been merged into main yet. Specifically make sure to use the *aarch64\_support* branch.

```
cd libelfmaster
git checkout aarch64_support
cd ./src
sudo ./make.sh
```

## Build and install Shiva

### Commands:

```
cd shiva
make
make shiva-ld
make patches
sudo make install
```

### Build results:

Shiva is a static ELF executable and installed to “/lib/shiva”. The Shiva modules are typically stored in “/opt/shiva/modules”. The example patches all live within “/git/shiva/modules/aarch64\_patches/”.

## Build and install example patches

Please see the “shiva/modules/aarch64\_patches/” directory. All of the example patches live here. Let us illustrate an example of building and testing one such patch on a program called ‘test\_rodata’.

### Commands:

```
cd shiva/modules/aarch64_patches/rodata_interposing
make
sudo make install
```

**Test the patch by setting the patch path and running “/lib/shiva” manually.**

```
$ SHIVA_MODULE_PATH=./ro_patch.o /lib/shiva ./test_rodata
```

Notice that the software prints the new string “The great arcanum”, per the patch. Yet when the program is executed without Shiva it executes with its old behavior.

```
$ ./test_rodata
```

### Install the patch permanently

You may also install the patch permanently with the Shiva prelinking tool. This tool updates the PT\_INTERP segment from “/lib/ld-linux.so” to “/lib/shiva”, and updates the dynamic segment with several new tags describing the path to the patch that should be loaded and linked at runtime: “/opt/shiva/modules/ro\_patch.o”.

```
$ /bin/shiva-ld -e test_rodata -p ro_patch.o -i /lib/shiva -s /opt/shiva/modules -o test_rodata.patched
```

Shiva now installs the patch in memory everytime it's executed

```
$ ./test_rodata.patched
```

The only discernible difference between test\_rodata.patched and test\_rodata are the PT\_INTERP segment modification and the PT\_DYNAMIC addition of two new entries describing the patch path. No actual code or data has changed within the ELF binary. Shiva performs all of the patching at runtime.

### 3 Writing patches with Shiva

#### The Shiva workflow

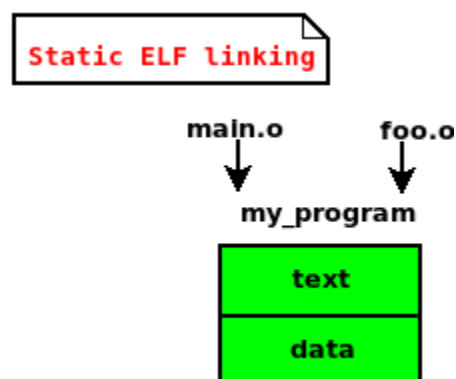
Before delving in to the use of Shiva, let us first explain the workflow of what the ELF compilation and linking process looks like before and after Shiva.

#### ELF Program compilation and linking example

Standard program compilation begins with a compiler like gcc; the source code files (i.e. main.o and foo.o) are compiled and then get linked (By “/bin/ld”) into a final output ELF executable my\_program.

#### *Static linking of objects*

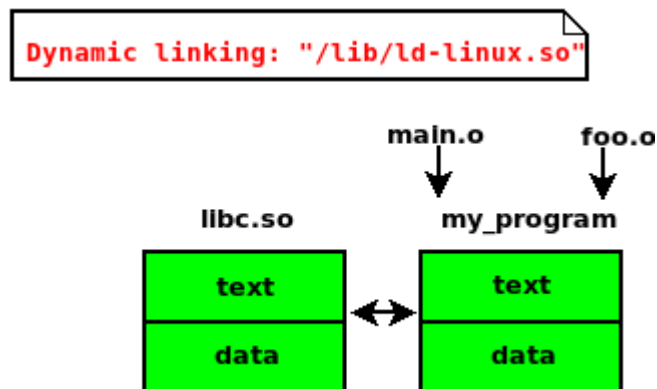
Image 3.0: static linking of two ELF relocatable objects with “/bin/ld”



Additionally these ELF relocatable object files contain calls to functions that live within ELF shared libraries. Once the object files (foo.o and main.o) are linked into an ELF executable (my\_program), additional Dynamic linking meta-data is created and stored into what is known as the PT\_DYNAMIC segment of the program header table. The PT\_DYNAMIC segment contains additional meta-data that is to be passed along to the Program interpreter at runtime. The program interpreter (aka: dynamic linker) is specified as a file path in the PT\_INTERP segment: “/lib/ld-linux.so”. When the program is executed the kernel loads and executes the interpreter program first: “/lib/ld-linux.so”. The interpreter loads and links the needed shared libraries (i.e. libc.so). The program is linked twice: once statically, and again dynamically.

### ***Dynamically linked executable***

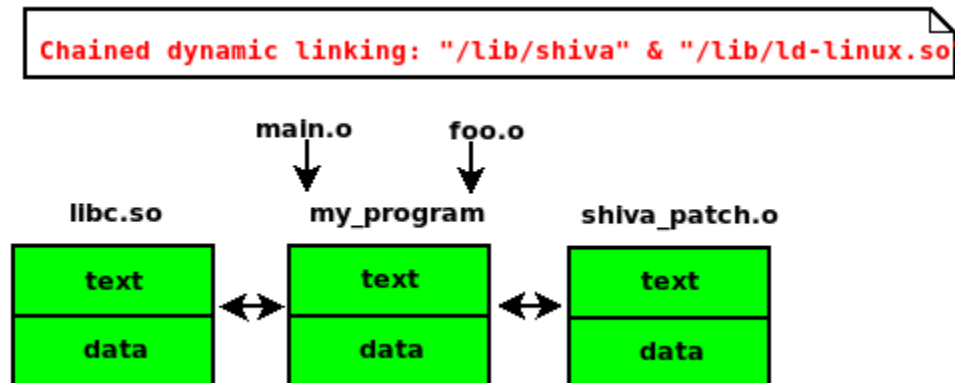
Image 3.1: Dynamically link libc.so in at runtime



A Shiva patch can be written in C and compiled as an ELF relocatable object file. In the same sense that “ld-linux.so” loads and links shared libraries (ELF ET\_DYN files), Shiva will load and link patch objects (ELF ET\_REL files) to re-write the program in memory just before execution.

### ***Dynamically patched executable***

Image 3.2: Chained linking with Shiva



## ELF Symbol interposition

The ELF format uses symbols to denote code and data. Program functions generally live in the `.text` section, and global variables live within the `.data`, `.rodata`, and `.bss` sections. Shiva makes use of the ELF relocation, section, and symbol data to allow patch developers to *interpose* existing symbols; in other words re-link functions and data that have symbols associated with them. As patch developers we will find this as a natural and beautifully convenient way to patch code and data.

### Citation 3.0: From “Oracle linkers and libraries guide”

“Interposition can occur when multiple instances of a symbol, having the same name, exist in different dynamic objects that have been loaded into a process. Under the default search model, symbol references are bound to the first definition that is found in the series of dependencies that have been loaded. This first symbol is said to interpose on the other symbols of the same name.”

## Patching an `.rodata` string (Simple first patch)

This patching exercise lives in “`modules/aarch64_patches/rodata_interposing`”. In the following example we are going to look at a simple program that prints a constant string “Arcana Technologies”. Constant data is read-only and is usually stored in the `.rodata` section of a program. The `.rodata` section is generally put into text segment, or a read-only segment that is adjacent to the text segment. A shiva module has it’s own `.rodata` section within it’s mapped text segment at runtime. Our goal with the following patch is to replace a read-only string by simply re-defining it in C.



Image 3.3: Original source code of program rodata\_test.c

```
#include <stdio.h>

const char rodata_string[] = "Arcana Technologies";

int main(void)
{
    printf("rodata_string: %s\n", rodata_string);
    exit(0);
}
```

NOTE: The source code to rodata\_test.c is only being shown for the sake of illustrating what the program does that we are patching. In many workflows the source code wouldn't even exist, and Shiva doesn't depend on or use the source in any way.

Image 3.4: Source code of patch object: ro\_patch.c

```
elfmaster@esoteric-aarch64:~/amp/shiva/modules/aarch64_patches/rodata_interposing$ cat ro_patch.c
const char rodata_string[] = "The Great Arcanum";
```

### ***Building the patch***

The patch source code “modules/aarch64\_patches/rodata\_interposing/ro\_patch.c” is a single line patch, redefining the symbol “rodata\_string[]”. To build this patch we can simply run the following gcc command to build the patch:

```
$ gcc -mmodel=large -fno-pic -fno-stack-protector -c ro_patch.c -o ro_patch.o
```

The ELF ET\_REL object: ro\_patch.o describes a symbol with the same exact name as the symbol `rodata_string` in the target executable. Shiva will see this when linking and it will link in the version of the symbol from our patch. This perfectly demonstrates the concept of symbol interposition in Shiva.

## ***Testing our patch: ro\_patch.o***

In this example we are patching the AArch64 ELF PIE executable: “modules/aarch64\_patches/rodata\_interposing/test\_rodata” Let’s first run the program normally.

```
$ ./test_rodata
rodata_string: Arcana Technologies
$
```

The program simply prints the string “rodata\_string: Arcana technologies”. To see if our patch worked we can invoke Shiva directly to load and link the executable with the patch at runtime. We must specify the path to our patch object with the SHIVA\_MODULE\_PATH environment variable.

```
$ SHIVA_MODULE_PATH=./ro_patch.o /lib/shiva ./test_rodata
rodata_string: The Great Arcanum
$
```

When executing ./test\_rodata with “/lib/shiva” as the primary loader it installs the specified patch, and the new rodata\_string[] value “The Great Arcanum” is printed to stdout. When we run ./test\_rodata without “/lib/shiva” it does not install the patch and the original string “Arcana Technologies” is printed.

## ***Using shiva-ld to prelink the patch***

The reality is that a user doesn’t want to invoke “/lib/shiva” every single time they want to run a program that needs a patch. This is why “/lib/shiva” is designed to be an ELF interpreter like “ld-linux.so”. We can use the Shiva prelinker “/bin/shiva-ld” to install the appropriate meta-data into the program we are patching:

- Update PT\_INTERP with the path to “/lib/shiva” (Replacing “/lib/ld-linux.so”).
- Add several custom entries to PT\_DYNAMIC describing the patch basename: “ro\_patch.o” and the module search path “/opt/shiva/modules”.

The following command will install the Shiva interpreter path and patch information into the ./test\_rodata binary.

```
$ shiva-ld -e test_rodata -p ro_patch.o -i /lib/shiva -s /opt/shiva/modules
```

This next command copies the patch file into the correct search path: “/opt/shiva/modules”

```
$ sudo cp ro_patch.o /opt/shiva/modules
```

Before we run ./test\_rodata, let’s take a quick look to see what modifications shiva-ld made to the executable:

Image 3.5: Requesting program interpreter is “/lib/shiva”

Program Headers:

Type	Offset FileSiz	VirtAddr MemSiz	PhysAddr Flags	Align
PHDR	0x0000000000000040 0x00000000000001c0	0x0000000000000040 0x00000000000001c0	0x0000000000000040 R	0x8
INTERP	0x0000000000000200 0x000000000000001b	0x0000000000000200 0x000000000000001b	0x0000000000000200 R	0x1
[Requesting program interpreter: /lib/shiva]				
LOAD	0x0000000000000000 0x0000000000000868	0x0000000000000000 0x0000000000000868	0x0000000000000000 R E	0x10000
LOAD	0x0000000000000d78 0x0000000000000298	0x0000000000001d78 0x00000000000002a0	0x0000000000001d78 RW	0x10000
DYNAMIC	0x0000000000000300 0x00000000000001d0	0x0000000000001200 0x00000000000001d0	0x0000000000001200 RW	0x8
LOAD	0x0000000000000300 0x0000000000000259	0x0000000000001200 0x0000000000000259	0x0000000000001200 RWE	0x1000
GNU_STACK	0x0000000000000000 0x0000000000000000	0x0000000000000000 0x0000000000000000	0x0000000000000000 RW	0x10
GNU_RELRO	0x0000000000000d78 0x0000000000000288	0x0000000000001d78 0x0000000000000288	0x0000000000001d78 R	0x1

In image 3.5 we can see that “/lib/shiva” is set as the new Interpreter path. The astute reader will also notice that there is a third PT\_LOAD segment marked RWE. The shiva-ld tool creates a new dynamic segment (As shown below in Image 2.3). In order to make room for this new and larger dynamic segment shiva-ld creates a new PT\_LOAD segment and updates the PT\_DYNAMIC segment program header so that it points into the new PT\_LOAD segment at 0x3000. The updated PT\_DYNAMIC segment is moved and stored in this new segment

Image 3.6: New dynamic segment contains 3 custom entries

```
Dynamic section at offset 0x3000 contains 29 entries:
Tag          Type          Name/Value
0x0000000000000001 (NEEDED)      Shared library: [libc.so.6]
0x000000000000000c (INIT)        0x5d0
0x000000000000000d (FINI)        0x81c
0x0000000000000019 (INIT_ARRAY)  0x10d78
0x000000000000001b (INIT_ARRAYSZ) 8 (bytes)
0x000000000000001a (FINI_ARRAY)  0x10d80
0x000000000000001c (FINI_ARRAYSZ) 8 (bytes)
0x00000000000000f5 (GNU_HASH)    0x260
0x0000000000000005 (STRTAB)      0x388
0x0000000000000006 (SYMTAB)      0x280
0x000000000000000a (STRSZ)      142 (bytes)
0x000000000000000b (SYMENT)     24 (bytes)
0x0000000000000015 (DEBUG)        0x0
0x0000000000000003 (PLTGOT)      0x10f78
0x0000000000000002 (PLTRELSZ)    144 (bytes)
0x0000000000000014 (PLTREL)      RELA
0x0000000000000017 (JMPREL)      0x540
0x0000000000000007 (RELA)        0x450
0x0000000000000008 (RELASZ)      240 (bytes)
0x0000000000000009 (RELAENT)     24 (bytes)
0x000000000000001e (FLAGS)       BIND_NOW
0x00000000000000fb (FLAGS_1)     Flags: NOW PIE
0x00000000000000fe (VERNEED)     0x430
0x00000000000000ff (VERNEEDNUM)  1
0x00000000000000f0 (VERSYM)      0x416
0x0000000000000018 (Operating System specific: 60000018) 0x121d0
0x0000000000000017 (Operating System specific: 60000017) 0x121e3
0x0000000000000019 (Operating System specific: 60000019) 0x121ee
0x0000000000000000 (NULL)        0x0
```

The above *image 3.6* shows the dynamic segment of the ELF binary: `test_rodata`, after we ran the `shiva-ld` tool on it. Notice the three *Operating System specific* entries at the tail end. The `readelf` utility doesn't know how to parse these custom entries. Here is what the actual entry types and values are:

```
(SHIVA_NEEDED)      Patch object: [ro_patch.o]
(SHIVA_SEARCH)      Search path: [/opt/shiva/modules]
(SHIVA_ORIG_INTERP) Original RTLD: [/lib/ld-linux-aarch64.so.1]
```

This data is needed by “`/lib/shiva`” at runtime so that it can locate and load the patch object, and the original dynamic linker (See Chained Linking in section x.x).

### ***Final outcome of patching test\_rodata***

Now every time that the `test_rodata` executable is ran it will invoke the Shiva interpreter which will in turn load the patch object “`/opt/shiva/modules/ro_patch.o`”.

```
$ ./test_rodata
rodata_string: The Great Arcanum
$
```

We can observe that the program `test_rodata` is now printing the patched version of `rodata_string[]` when it is ran. This patch may appear permanent, but in effect the patch is actually being installed at runtime by “/lib/shiva” everytime the program runs.

### ***Current limitations of patching const data***

There are patching scenarios with *const* data that fail with symbol interposition due to code optimizations with read-only data. In the previous example we illustrated how to patch a read-only global variable defined in C as:

```
const char rodata_string[] = “Arcana Technologies”;
```

The target program gets re-linked to use the patch version of `rodata_string`. Using symbol interposition to overwrite `.rodata` variables works perfectly unless the read-only value is optimized out of memory and stored only in a register. Let’s look at the following example:

### **Image 3.7: C code illustrating a read-only global variable**

```
const int rodata_val = 5;

int main(void)
{
    printf(".rodata string: %d\n", rodata_val);
    exit(0);
}
```

After compiling the code above with `gcc`, even after all optimizations are disabled, you will get code similar to the following AArch64 assembly.

### **Image 3.8: Code optimization of read-only variable in aarch64 assembly**

```
Dump of assembler code for function main:
0x0000aaaaaaaa774 <+0>:      stp     x29, x30, [sp, #-16]!
0x0000aaaaaaaa778 <+4>:      mov     x29, sp
=> 0x0000aaaaaaaa77c <+8>:      mov     w1, #0x5                                // #5
0x0000aaaaaaaa780 <+12>:     adrp    x0, 0xaaaaaaaa000
0x0000aaaaaaaa784 <+16>:     add     x0, x0, #0x840
0x0000aaaaaaaa788 <+20>:     bl      0xaaaaaaaa660 <printf@plt>
0x0000aaaaaaaa78c <+24>:     mov     w0, #0x0                                // #0
0x0000aaaaaaaa790 <+28>:     bl      0xaaaaaaaa610 <exit@plt>
```

In the code above we can see that the value 5 is being copied as an immediate value into a register. This is an optimization that removes the need for an `adrp/add/ldr` instruction trio, thus eliminating two instructions and the need for memory access. This optimization is inauspicious for symbol interposition based patching since the actual `.rodata` variables memory is not being accessed and therefore there is no linking code to update. Instead there is only an instruction: `“mov w1, #0x5”`. Clearly this instruction can be re-encoded rather simply, but what would a patch look like for this? For the curious reader, move ahead to the section titled *“ELF Transformations & Function splicing”*.

## Symbol interposition on functions

Shiva gives patch writers the ability to replace a function trivially using symbol interposition. We’ve all seen userland rootkits that re-write `libc.so` functions by introducing a preloaded library with a new version of the function. In the same spirit Shiva allows patch writers to replace any function in the target ELF executable with a symbol of type `STT_FUNC` and symbol bindings of `STB_GLOBAL` or `STB_WEAK`. The only exception is that the function `main()` cannot be replaced, although future support is on the way, as it depends on the `glibc` initialization code that transfers control to `main` from `_start`.

Let’s get started with a simple example of replacing a function called `foo()`.

### ***Patch exercise 2: Replacing function `foo()`***

```
$ cd shiva_examples/function_interposing
```

Image 3.9: Original source code of the binary `test_foo`

```
elfmaster@esoteric-aarch64:~/amp/shiva_examples/function_interposing$ cat test_foo.c
#include <stdio.h>

int foo(void)
{
    printf("I am the original foo() function\n");
    return 1;
}

int main(void)
{
    int ret;

    ret = foo();
    printf("Return value: %#x\n", ret);
}
elfmaster@esoteric-aarch64:~/amp/shiva_examples/function_interposing$
```

From the original source code shown in *Image 3.9* we can clearly see that `foo()` is a global function called by `main()`. In order to replace `foo()` with our own version we can simply re-write the function by name in our patch source code.

### Image 3.10: `foo_patch.c` source code

```
elfmaster@esoteric-aarch64:~/amp/shiva_examples/function_interposing$ cat foo_patch.c
#include <stdio.h>

int foo(void)
{
    printf("I am the new function foo()\n");
    return 0x31337;
}
elfmaster@esoteric-aarch64:~/amp/shiva_examples/function_interposing$
```

Shiva handles all of the linking at runtime for the patch, including shared library calls. Shiva works in conjunction with the `ld-linux.so` interpreter to accomplish these goals. All call instructions (*i.e. branch with link*) are given a PLT entry within the patch module at runtime. The patch has it's own PLT/GOT and the GOT is filled in at runtime with the address to every function (*Both in and out of the module*) that are being called. Shiva handles all of the runtime relocations prior to passing control to `ld-linux.so` except for when the relocation references symbolic code or data that live within a shared library. A call to `libc:printf()` from within the patch code have it's own respective GOT entry. The address of `printf()` won't be known until `ld-linux.so` has mapped the shared libraries into memory and processed their

relocations. To handle this scenario Shiva incorporates a *Post Linker* which waits until ld-linux.so has processed all of the symbol relocations for each shared library, and then finalizes fixing up the patch modules GOT with the addresses to each respective shared library symbol.

## Shiva Post Linker

The Shiva Post Linking Phase is a great example of what Shiva refers to as Cross-ELF-Relocations (*Defined as a relocation who's computation relies on the results of a secondary relocation solved by an entirely separate runtime linker - One linker must wait on the other to satisfy the Cross-Relocation*) In particular though, the Shiva-Post-Linker is a linking mechanism that delays certain relocations from being processed until the standard RTLD "ld-linux.so" has finished mapping in each shared library and processing their respective relocations. In the event that Shiva has to fill in the PLT/GOT entry to resolve a function, such as printf() in the patch code above for foo(), it must rely on the dynamic linker to load and link libc.so:printf() first. After ld-linux.so is finished, it must somehow control must somehow be transferred back to Shiva, particularly to the function shiva\_post\_linker(). To make this happen we actuallyTo give some context, here is a screenshot of the shiva post linkers source code.

### Image 3.11: shiva\_post\_linker.c comments

```
#include "shiva.h"

/*
 * The aarch64 post linker in Shiva works by hooking AT_ENTRY early on (In
 * shiva_module.c:apply_relocation), so that it is set to &shiva_post_linker()
 * instead of the &_start() of the target program. Let's look at the few lines of
 * code leading up to 'br _start' in ld-linux.so:
 *
 * ld-linux.so code:
 *
 * 0x1001240: bl      0x100dab8 ; branch with a link sets x30 to 0x1001244
 * 0x1001244: adrp    x0, 0x100d000
 * 0x1001248: add     x0, x0, #0xc08
 * 0x100124c: br      x21 ; jump to _start() has been hooked to jump to &shiva_post_linker
 *
 * Control is transferred to our function below, which runs after ld-linux.so has loaded
 * and linked it's libraries, therefore we use shiva_maps_get_so_base() to acquire the
 * base address of the library for the symbol we are resolving. We resolve the symbol
 * value by applying the delayed relocation value to the rel_unit.
 *
 * Once we are done, we reset $x21 directly with the value of the real &_start.
 * shiva_post_linker() returns... not to the instruction after '0x100124c: br      x21'
 * because no branch-link was set. Therefore we return to 0x1001244, and with
 * an updated $x21 we now jump to &_start
 *
 * shiva_post_linker() must specifically handle each linker architecture.
 */
```



In the above *image 3.11* the comments describe how Shiva actually replaces the auxiliary vector value for AT\_ENTRY on the stack, which normally contains the address to \_start() in the ELF executable that is running, and ld-linux.so passes final control to this address. Shiva takes advantage of this and hooks AT\_ENTRY with the address of &shiva\_post\_linker(); The post linker introduces the concept of *Delayed relocations*. It is simply the concept that the linker notes a relocation entry for delayed fixups; meaning delayed until the ld-linux.so finishes loading and linking all of the shared libraries, at which point control is passed back to &shiva\_post\_linker() to apply the delayed relocation entries.

Image 3.12: shiva\_post\_linker() source code

```
void
shiva_post_linker(void)
{
    static struct shiva_module_delayed_reloc *delay_rel;
    static uint64_t base;

    TAILQ_FOREACH(delay_rel, &ctx_global->module.runtime->tailq.delayed_reloc_list, _linkage) {
        if (shiva_maps_get_so_base(ctx_global, delay_rel->so_path, &base) == false) {
            fprintf(stderr, "Failed to locate base address of loaded module '%s'\n",
                    delay_rel->so_path);
            exit(EXIT_FAILURE);
        }
        shiva_debug("Post linking '%s'\n", delay_rel->symname);
        /*
         * Apply the final relocation value on our delayed
         * relocation entry.
         */
        *(uint64_t *)delay_rel->rel_unit = delay_rel->symval + base;

        shiva_debug("%#lx:rel_unit = %#lx + %#lx (%#lx)\n", delay_rel->rel_addr,
                    delay_rel->symval, base, delay_rel->symval + base);
    }

    shiva_debug("Transferring control to %#lx\n", ctx_global->ulexec.entry_point);
    test_mark();

    /*
     * Mark the text segment as writable now that there won't
     * be any final fixups in the modules .text.
     */
    if (mprotect(ctx_global->module.runtime->text_mem,
                ELF_PAGEALIGN(ctx_global->module.runtime->text_size,
                              PAGE_SIZE),
                PROT_READ|PROT_EXEC) < 0) {
        perror("mprotect");
        return false;
    }

    __asm__ __volatile__ ("mov x21, %0" :: "r"(ctx_global->ulexec.entry_point));
    return;
}
```

In *Image 3.11* above, The `shiva_post_linker()` source code illustrates how it handles delayed relocations. Particularly (S + B) which is symbol value + base address. The final relocation value is stored in the patch modules GOT entry for the shared library function that is being called. The execution flow goes something like this:

[shiva runtime linker] → [ld-linux.so linker] → [shiva\_post\_linker] → [\_start() in exe]

We reset the value in register x21 back to the original entry point of the executable in `&_start()`.

## Relocations and symbol data in `foo_patch.o`

Without further contemplation lets jump right into the patch directory:  
“shiva\_examples/function\_interposing”

Image 3.12: View the patch files in directory “function\_interposing”

```
elfmaster@esoteric-aarch64:~/amp/shiva_examples/function_interposing$ ls
foo_patch.c foo_patch.o Makefile test_foo test_foo.c
elfmaster@esoteric-aarch64:~/amp/shiva_examples/function_interposing$ ./test_foo
I am the original foo() function
Return value: 0x1
elfmaster@esoteric-aarch64:~/amp/shiva_examples/function_interposing$ cat foo_patch.c
#include <stdio.h>

int foo(void)
{
    printf("I am the new function foo()\n");
    return 0x31337;
}
```

Notice the patch above ‘`foo_patch.c`’ is simply a re-write of the function `foo()`. At runtime Shiva will place this new version of `foo()` into the patch modules text segment. A quick look at it’s relocation entries:

Image 3.13: Relocation entries for program `./test_foo`

```
elfmaster@esoteric-aarch64:~/amp/shiva_examples/function_interposing$ readelf -r foo_patch.o
Relocation section '.rela.text' at offset 0x218 contains 4 entries:
  Offset             Info             Type             Sym. Value      Sym. Name + Addend
00000000000008      000200000113  R_AARCH64_ADR_PRE 0000000000000000 .text + 28
0000000000000c      000200000115  R_AARCH64_ADD_ABS 0000000000000000 .text + 28
00000000000014      000c0000011b  R_AARCH64_CALL26  0000000000000000 puts + 0
00000000000028      000500000101  R_AARCH64_ABS64   0000000000000000 .rodata + 0
elfmaster@esoteric-aarch64:~/amp/shiva_examples/function_interposing$
```

The relocations for our patch `foo_patch.o` will be processed and applied by Shiva at runtime. Here is an explanation of the relocations for our patch, while not yet discussing the re-linking of the target executable that has no viable relocation meta-data for Shiva.

- The first relocation is to be applied at offset `0x8` within the `.text` section of our module. This relocation is symbolically referencing `.text + 28`, which is going to eventually contain the address to `.rodata + 0`, where the string “I am the new function `foo()`” lives. To be specific, this relocation is re-encoding an `adrp` instruction to return the page address of the `.text` encoding at `0x28`

*NOTE: Shiva refers to a relocation such as this, as a `.text on .text` relocation. Meaning that the relocation (`.rela.text`) table applies to the `.text` section fixups, and when one of those `.text` fixups references a symbol in the `.text`; i.e. symbolically referencing another place within the `.text`. This becomes important to Shiva when it's using more advanced features such as function splicing transforms. Therefore “`.text on .text` relocation” :)*

- The second relocation is adding the offset of the `.text` encoding so that the following `ldr` instruction can indirectly access the address from the `.text` encoding and store it into a register as a pointer to the string “I am the new function `foo()`”.
- The third relocation is a `CALL26` to re-encode the `b/` instruction with the 26bit offset to the patches PLT entry for `libc.so:puts()`.
- The last relocation is the one that fills in the `.text` encoding that should contain the address of `.rodata + 0x28`.

*NOTE: The `.text` encodings often act as an indirect reference to something like a `GOT[]` does, in fact... The `binutils` linker “`/bin/ld`” generally moves these `.text` encodings into the `.got[]` when the final executable is built. However it is not a necessary linking procedure. Shiva modules do actually have a designated `GOT` in the modules data segment at runtime and is used exclusively for `PLT/GOT` linking of the `CALL26` relocations.*

Let's take a look at the patch object file disassembly for function `foo()` and compare the instruction offsets to those specified in the relocations above.

Image 3.14: Disassembly of foo\_patch.o:foo() before relocation happens

```
foo_patch.o:      file format elf64-littleaarch64
I
Disassembly of section .text:
0000000000000000 <foo>:
 0: a9bf7bfd      stp     x29, x30, [sp, #-16]!
 4: 910003fd      mov     x29, sp
 8: 90000000      adrp    x0, 0 <foo>
 c: 91000000      add     x0, x0, #0x0
10: f9400000      ldr     x0, [x0]
14: 94000000      bl      0 <puts>
18: 528266e0      mov     w0, #0x1337                      // #4919
1c: 72a00060      movk    w0, #0x3, lsl #16
20: a8c17bfd      ldp     x29, x30, [sp], #16
24: d65f03c0      ret
```

The code shown above in *Image 3.14* is the objdump output of our replacement *foo()* function. Resolving relocations to build our own modules runtime image is based on the relocatable nature of the object file and the symbolic scope that Shiva uses to re-link the process image. This code can be relocated fairly easy by Shiva's standard linking capabilities. The next part to solving the patching at runtime is re-linking the code in the target executable (*in memory*) so that any calls to *foo()* are replaced with calls to the new location of *foo()* within the patches executable image. External re-linking can be a trifle difficult at times due to a lack of relocation records describing how to re-link *.text* code.

### **Shiva external re-linking of the ELF executable**

Shiva's initial linking job is to ensure that a runtime image can be setup for the patch module, in this case it is *foo\_patch.o*. The ELF sections in this file are copied into their respective memory segments that Shiva creates with *mmap*; a text segment (*.text*, *.plt*, *.rodata*, *.shiva\_transform*, *.shiva\_CFG*) and a data segment (*.got*, *.data*, *.bss*). Relocations are driven by section offsets, and thus Shiva creates an internal data structure pointing to where each section lives within the patches executable environment. (*i.e. .text, .data, .bss section within the modules text segment*). Shiva sets up an executable process image for the patch right next to the target executable in memory. Now that the patch code is ready for execution, the target program we are patching hasn't yet been re-linked. Historically ELF executables have never stored the more granular *ET\_REL* style relocations because they aren't necessary as the program has already been linked into an executable. The only relocation data in an executable is for the initialization code or dynamic linker to resolve global symbols from shared objects. In this particular case Shiva needs to know the location of each call instruction to *foo()* and re-link the instruction to the replacement *foo()* from our *foo\_patch.o* module. Ideally Shiva would have in this case an *R\_AARCH64\_CALL26* relocation, but we haven't really needed such relocation types as this one outside of linking object multiple files. Shiva re-links object files into executables at

runtime, as it is a patching engine. Shiva scans the `.text` section at runtime to build all of the CFG data. See `shiva_analyze.c:shiva_find_calls()` which very early on parses every instruction in the target executables `.text` section generating calls/xrefs to code and data. This can be seen in the following function `shiva_module.c:apply_external_patch_links()` -- re-linking the target executable's instructions to patch data and patch code. By the time you read this user-manual though, all of the CFG analysis will be generated in the Prelinker: "shiva-ld" a tool which stores all of the control flow graph data into a custom ELF section in the patch module (i.e. ELF section called `.shiva.CFG`). At runtime Shiva will simply read the CFG data in from this custom section who's meta-data provides the correct relocations for where in the target executable we must re-link. This CFG and relocation data is generated by the Shiva prelinker: shiva-ld, which only has to run once vs. everytime Shiva runs. This will reduce Shiva's load time dramatically.

### ***Patch example 2: Apply Function interposing patch, replace foo()***

We've spent the last little while discoursing on Shiva's internals to give some insights into how ELF symbolic resolution, relocations, and cross relocations work together to support the JIT re-writing, re-encoding and transformation of the process image: Merging the patch and the executable into a single process image, eternally betrothed through linkage.

#### ***Image 3.15: Patch example 2, Replacing function foo()***

```
elfmaster@esoteric-aarch64:~/amp/shiva_examples/function_interposing$ make prog
# Build the program we are patching
gcc -O0 test_foo.c -o test_foo
elfmaster@esoteric-aarch64:~/amp/shiva_examples/function_interposing$ readelf -l test_foo | grep Requesting
[Requesting program interpreter: /lib/ld-linux-aarch64.so.1]
elfmaster@esoteric-aarch64:~/amp/shiva_examples/function_interposing$ ./test_foo
I am the original foo() function
Return value: 0x1
elfmaster@esoteric-aarch64:~/amp/shiva_examples/function_interposing$ SHIVA_MODULE_PATH=./foo_patch.o /lib/shiva ./test_foo
I am the new function foo()
Return value: 0x31337
elfmaster@esoteric-aarch64:~/amp/shiva_examples/function_interposing$ ./test_foo
I am the original foo() function
Return value: 0x1
elfmaster@esoteric-aarch64:~/amp/shiva_examples/function_interposing$
```

In the example above, *Image 3.15*, we illustrate that the target ELF binary: `test_foo`, is not using Shiva as the interpreter, but rather the standard `"/lib/ld-linux.aarch64.so.1"`. We want to test our patch out before prelinking the patch meta-data with Shiva-ld. Again we can invoke `"/lib/shiva"` directly and it assumes responsibility for loading the executable you are patching, rather than the kernel doing it

***NOTE: See grugqs classic paper on engineering userland execve implementation for anti-forensics. So much mileage out of this great technique over the years.***



### Shiva-ld tool. Prelink executable ./test\_foo with foo\_patch.o

*Image 3.16: Prelinking the patch: foo\_patch.o to the executable: test\_foo*

```
elfmaster@esoteric-aarch64:~/amp/shiva_examples/function_interposing$ make prelink
# Pre-link the program we are patching with the proper interpreter and patch meta-data
"/usr/bin/shiva-ld" -e test_foo -p foo_patch.o -i /lib/shiva -s /opt/shiva/modules -o test_foo
[+] Input executable: test_foo
[+] Input search path for patch: /opt/shiva/modules
[+] Basename of patch: foo_patch.o
[+] Output executable: test_foo
Writing out original interp path: /lib/ld-linux-aarch64.so.1
Finished.
elfmaster@esoteric-aarch64:~/amp/shiva_examples/function_interposing$ readelf -l test_foo | grep Requesting
[Requesting program interpreter: /lib/shiva]
elfmaster@esoteric-aarch64:~/amp/shiva_examples/function_interposing$
```

### Execute “test\_foo” after shiva-ld has prelinked it

*Image 3.17: Executing test\_foo with Shiva as ELF interpreter*

```
elfmaster@esoteric-aarch64:~/amp/shiva_examples/function_interposing$ ./test_foo
I am the new function foo()
Return value: 0x31337
elfmaster@esoteric-aarch64:~/amp/shiva_examples/function_interposing$ ./test_foo
I am the new function foo()
Return value: 0x31337
elfmaster@esoteric-aarch64:~/amp/shiva_examples/function_interposing$ shiva -u ./test_foo
I am the original foo() function
Return value: 0x1
elfmaster@esoteric-aarch64:~/amp/shiva_examples/function_interposing$
```

Notice from *Image 3.17* that the ELF program test\_foo executes and calls the replacement `foo()` function correctly from within the `foo_patch.o` module. The test\_foo binary has been shiva-prelinked and contains the updated PT\_INTERP segment with “/lib/shiva” replacing “/lib/ld-linux-aarch64.so.1”. Every time the program executes the kernel invokes Shiva as the interpreter, which in turn performs its LEJIT operations (Linking & Encoding, Just in time). The last command in *Image 3.17* is note worthy too:

```
$ shiva -u ./test_foo
I am the original foo() function
Return value: 0x1
$
```

Notice that Shiva is invoked directly this time and we specify the ‘-u’ flag which essentially means “userland-exec only, don’t apply patches”. The program “test\_foo” now executes

without the patches installed at runtime. This illustrates the flexibility of a modular patching system well, as it's workflow is more resilient than static patching.

## **Symbol interposition on global data: .rodata, .bss, .data**

Thus far Shiva has demonstrated the ability to re-write global functions and global data by name. ELF Symbolic data of any type can be re-defined in a Shiva patch, whether it be a function or a global variable. Let us illustrate a patch that re-writes both global data and several functions all in the same patch, as there is no limitation to the number of global variables and functions that can be interposed.

Shiva doesn't yet support re-writing thread local storage variables, but support for this is on the road map.

## **Re-declaring the size of global variables**

When a variable is re-declared or re-defined in a Shiva patch, the target program is re-linked to reference the new global variable which exists somewhere within the Shiva patch module. Therefore it stands to reason that a variable can be redefined in size, and type. In this example we will demonstrate a patch that re-sizes a *.bss* global buffer in order to fix a ridiculous and hand-crafted vulnerability which results in local privilege escalation.

### ***Fixing .bss overflow by increasing buffer size***

Change directories to "shiva\_examples/bss\_vuln". Let's take a look at the original source code for this vulnerable program.

*Image 3.18: bss\_vuln.c source code*

```

#include <stdint.h>
#include <stdlib.h>
#include <stdio.h>
#include <sys/stat.h>

#define MAX_LEN 32

uint8_t uid;
uint8_t bss_buffer[16];

int main(int argc, char **argv)
{
    if (argc < 2) {
        fprintf(stderr, "Usage: %s <file_payload>\n", argv[0]);
        return 0;
    }
    uid = getuid();

    printf("uid: %d\n", uid);

    strncpy(bss_buffer, argv[1], 32);

    printf("Setting uid: %d\n", uid);
    setuid(uid);
    system("/bin/bash");
}

```

In *image 3.18* we can see the original source code to the program “shiva\_examples/bss\_vuln/bss\_vuln.c”. This program illustrates how the function *strncpy* pads the remaining length of a buffer with null bytes and how this behavior can lead to a *.bss* overflow that overwrites the bss variable *uint8\_t uid* with the value 0, which is then passed to *setuid()* before a call to *system()*. In our somewhat unrealistic example, we aim to re-size the variable *bss\_buffer[16]* to *bss\_buffer[32]* to prevent the 0 padded *.bss* overflow.

### *Image 3.19: Running the vulnerable bss\_vuln program*

```

elfmaster@esoteric-aarch64:~/amp/shiva_examples/bss_overflow$ ./bss_vuln hello
uid: 232
Setting uid: 0
root@esoteric-aarch64:~/amp/shiva_examples/bss_overflow# whoami
root
root@esoteric-aarch64:~/amp/shiva_examples/bss_overflow#

```

Running this program, and passing in a string length of less than 32 bytes will cause the bug to be triggered and for dramatic effect we can see the pop of a root shell in *Image 3.19*. And as already shown in the original source code, *bss\_buffer* is an uninitialized static global



variable that lives in the `.bss`. Let's confirm that this global variable does indeed exist within the `.bss` of the target executable before we demonstrate our patch.

*Image 3.20: Verifying `bss_buffer` variable exists in target executable*

```
elfmaster@esoteric-aarch64:~/amp/shiva_examples/bss_overflow$ readelf -s bss_vuln | grep bss_buffer
76: 00000000000011018 16 OBJECT GLOBAL DEFAULT 22 bss_buffer
elfmaster@esoteric-aarch64:~/amp/shiva_examples/bss_overflow$ readelf -S bss_vuln | grep 22
[22] .bss NOBITS 00000000000011010 00001010
elfmaster@esoteric-aarch64:~/amp/shiva_examples/bss_overflow$
```

In *Image 3.20* we confirm that a `.bss` variable `bss_buffer[16]` does exist and its bindings are `STB_GLOBAL`. We can fix this vulnerability by simply re-defining `bss_buffer` as a 32 byte length buffer. Patching the program `"bss_vuln"` is straightforward, watch...

*Image 3.21: Patching the `bss_vuln` vulnerability by re-defining `bss_buffer`*

```
elfmaster@esoteric-aarch64:~/amp/shiva_examples/bss_overflow$ cat bss_patch.c
#include <stdint.h>

uint8_t bss_buffer[32]; // extend buffer from 16 to 32bits
elfmaster@esoteric-aarch64:~/amp/shiva_examples/bss_overflow$ make patch
gcc -mmodel=large -fno-pic -I ../ -fno-stack-protector -c bss_patch.c
elfmaster@esoteric-aarch64:~/amp/shiva_examples/bss_overflow$ shiva-ld -e bss_vuln \
> -i /lib/shiva -p bss_patch.o -s /opt/shiva/modules/ -o bss_vuln
[+] Input executable: bss_vuln
[+] Input search path for patch: /opt/shiva/modules/
[+] Basename of patch: bss_patch.o
[+] Output executable: bss_vuln
Writing out original interp path: /lib/ld-linux-aarch64.so.1
Finished.
elfmaster@esoteric-aarch64:~/amp/shiva_examples/bss_overflow$ sudo cp bss_patch.o /opt/shiva/modules
[sudo] password for elfmaster:
elfmaster@esoteric-aarch64:~/amp/shiva_examples/bss_overflow$ ./bss_vuln hello
uid: 232
Setting uid: 232
elfmaster@esoteric-aarch64:~/amp/shiva_examples/bss_overflow$
```

As shown above in *Image 3.21* a simple patch re-declaring the size of `bss_buffer[16]` to `bss_buffer[32]` is compiled and pre-linked in just two commands. The program `bss_vuln` is now linked to the `bss_buffer[32]` and doesn't overflow anymore at the call to `strncpy()`.

## **Cross-Relocation with `.bss` relinking**

For those interested in understanding the internals of `.bss` variable relocation in Shiva, please keep reading to understand a key Shiva feature known as *Cross Relocations*.

The `.bss` is uninitialized data and doesn't take up any space in the ELF file. ELF PIE binaries use `R_AARCH64_RELATIVE` relocation's to fixup the `.got` with the correct address to the `.bss` variable after it's been allocated at runtime. In order for Shiva to re-link the binary to use the new `.bss` variable in the patch it must update the `.got` entry with the address to the new variable living within the patches runtime image. The RTLD "ld-linux.so" will process the `R_AARCH64_RELATIVE` relocation's and overwrite the `.got` entry for the `.bss` variable. because the RTLD runs after Shiva and therefore updates the `.got` after Shiva. This introduces a little problem that is solved by a concept that we call *Cross Relocation*. It is an almost inevitable by-product of chaining two dynamic linkers together. Cross relocation refers to the idea that Shiva and ld-linux.so (Two linkers in the same process) must synchronize relocation data and work together to solve a relocation. In the case of linking `.bss` variables Shiva modifies the relocation record in memory. Specifically the `r_addend` value to reflect the location of the new `.bss` variable within the patch image. Let's examine this up close.

Image 3.22: Lookup the address of the `bss_buffer` symbol

```
elfmaster@esoteric-aarch64:~/amp/shiva_examples/bss_overflow$ readelf -s bss_vuln | grep bss_buffer
76: 00000000000011018 16 OBJECT GLOBAL DEFAULT 22 bss_buffer
elfmaster@esoteric-aarch64:~/amp/shiva_examples/bss_overflow$
```

The `bss_buffer` variable is at address `0x11018` (As shown in Image 3.22 above). This address exists past the end of the data segment on disk and will be allocated by the kernel at ELF load time.

Image 3.23: Find the relative relocation for `bss_buffer` by address

```
elfmaster@esoteric-aarch64:~/amp/shiva_examples/bss_overflow$ readelf -r bss_vuln | grep 11018
0000000010fc8 0000000000403 R_AARCH64_RELATIV 11018
elfmaster@esoteric-aarch64:~/amp/shiva_examples/bss_overflow$
```

The `R_AARCH64_RELATIVE` relocation in Image 3.23 is going to compute the relocation computation (`B + A`):

The `r_offset` (*The address to be patched*) is `0x10fc8`. The `r_addend` value is `0x11018`. The base must be added with the `r_addend` and stored at the location specified by `r_offset`. The RTLD will apply this like so:

```
*(uint64_t*)&0x10fc8[0] = 0x11018 + base_address
```

Shiva wants to redirect all references to `bss_buffer` from the old location `0x11018` to the new location within the patch object, who's address won't be known until runtime. At runtime Shiva calculates the offset from the executable base address to the patches `bss_buffer` variable. Shiva overwrites the `r_addend` field of the `R_AARCH64_RELATIVE` relocation from `0x11018` to the new offset of the patch `bss_buffer` variable.

## ***The algorithm for cross relocations on .bss variables***

1. locate the R\_AARCH64\_RELATIVE relocation who's r\_addend is equal to the offset of the original .bss variable.
2. Calculate the offset of the new patch .bss variable from the base of the executable:  
 $\text{new\_var\_addr} - \text{executable\_base} - 4$
3. Store the offset as the updated r\_addend field in the relocation entry

## **Redeclaring global data types, signedness, and size**

It is common to change the data-type, signedness or size of a variable in order to fix a bug. This is therefore a common requirement in the world of micropatching binaries. Shiva will create a new variable matching the correct data-type and size and relink the program to the new variables. This may or may not have expected results since Shiva doesn't recompile the executable code that is reading or writing to that data. As it stands there are no limitations on changing the integer type and storage location of any global variable with the exception of TLS data. Any STT\_OBJECT with STB\_GLOBAL bindings can be re-linked to any other STT\_OBJECT/STB\_GLOBAL variable within a defined patch. Support for patching STB\_LOCAL binded variables and functions will be supported in the future.

### ***Redeclaring global integer signedness***

When a patch re-declares a global variable's signedness, it will create a new global variable within the patch, and all code within that same patch will be compiled into code that treats the variable by it's new signedness. The code within the executable being patched will be re-linked to use the new global variable, but it's code won't be updated to reflect the change in the variables signedness and therefore the final outcome is somewhat ambiguous.

**Old definition:** `int data_var = 5;` (Defined within the ELF executable program)

**New definition:** `unsigned int data_var = 5;` (Defined within the ELF patch)

**Outcome Results:** Original program code will still see the new variable as signed. New program code introduced by the patch will see the variable as unsigned.

**Outcome Description:** Shiva will allocate `sizeof(int)` bytes in the `.data` section of the patch and relink the executable to use the new `data_var` variable. The signedness was changed from signed to unsigned, but only the code within the patch itself (Assuming there is any) will respect the new signedness since it's code was compiled to see an *unsigned int data\_var = 5*; whereas the code in the executable being patched was compiled when `data_var` was declared as a signed value, and therefore it's computations and read/write accesses will still be treating it as signed.

## ***Redeclaring global storage type***

There may be times when the patch operator wants to re-declare an uninitialized global variable (i.e. *.data*) as const (i.e. *.rodata*). Or change an uninitialized *.bss* variable to a *.data* variable, etc. Shiva allows for the re-linking of any STT\_OBJECT type symbols that are globally binded (STB\_GLOBAL).

### ***Redeclaring a global .data variable as a constant***

Old definition: `int data_var = 5;`

New Definition: `const int data_var = 5;`

**Outcome results:** The *data\_var* variable will become a read-only variable, constant.

**Outcome description:** Shiva will create it's own *.rodata* section within the patches text segment at runtime. A 32bit integer called *data\_var* will be allocated in the patches *.rodata* section, and all references to the old *data\_var* variable within the executable will be re-linked by Shiva to reflect the location of the new read-only *data\_var* within the patch modules text-segment. The original *data\_var* variable still exists, its simply is no longer referenced.

**NOTE:** *Shiva refers to symbols no longer being used (Such as the old data\_var variable) as "defunct symbols".*

## **Patching STB\_LOCAL variables**

## **Using the extern keyword in your patch code**

## **Symbolic patching of stripped ELF's**