Constructing ELF Metadata

BerlinSides 0x3

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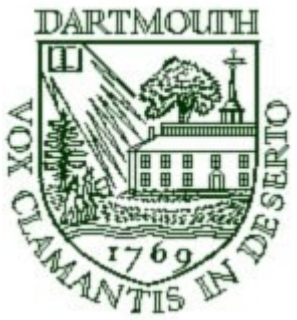

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This Talk in One Minute

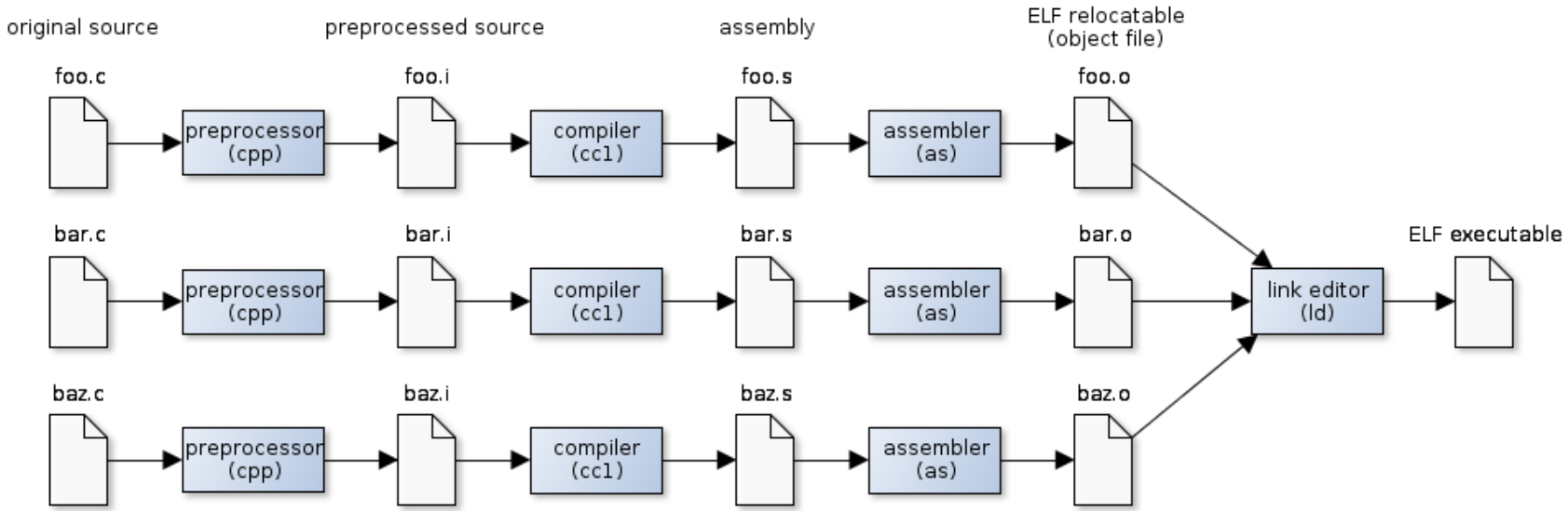
- ”Deep magic” before a program can run
  - ELF segments, loading, relocation,
- ”Deeper magic” to support dynamic linking
  - Dynamic symbols, loading of libraries
- Many pieces of code – enough to **program anything** (Turing-complete)
  - In perfectly **valid** ELF **metadata** entries alone
- Runs before most **memory protections** are set for the rest of runtime
- Runs with access to **symbols** (ASLR? what ASLR?)

The Quest

- ELF background
- Prior work with abusing ELF
- Everything you need to know about ELF metadata for this talk
- Branfuck to ELF compiler
- Relocation entry backdoor
  - Demo exploit

ELF
Executable and Linking Format

- How gcc toolchain components communicate
  - Assembler
  - Static link editor
  - **Runtime link editor (RTLD)**
  - Dynamic loader



ELF Components

- Architecture/version information
- Symbols
  - Symbol names (string table)
- Interpreter location (usually ld.so)
- Relocation Entries
- Debugging information
- Constructors/deconstructors
- Dynamic linking information
- ….
- Static/initialized data
- Code
  - Entrypoint

ELF Section

- All data/code is contained in ELF sections
  - Except ELF, section, and segment headers
- 1 section <---> 1 section header
  - Describes type, size, file offset, memory offset, etc, for linker/loader
- Most sections contain one of
  - Table of a single type of metadata
  - Null terminated strings
  - Mixed data (ints, long, etc)
  - Code

Sections of interest

- Symbol table (.dynsym)
- Relocation tables (.rela.dyn, .rela.plt)
- Global offset talbe (.got)
- Procedure linkage table (.got.plt)
- Dynamic table (.dynamic)

Symbol table

- Info to (re)locate symbolic definitions and references
  - For variables/functions imported/exported
- Example symbols in libc:

```
Num:          Value          Size  Type        Bind        Vis      Ndx Name
7407: 0000000000376d98     8  OBJECT  GLOBAL DEFAULT  31  stdin
7408: 00000000000525c0    42  FUNC      GLOBAL DEFAULT  12  putc
```

- Symbol definition for 64-bit architecture:

```
typedef struct {
    uint32_t      st_name;
    unsigned char st_info;
    unsigned char st_other;
    uint16_t      st_shndx;
    Elf64_Addr    st_value;
    uint64_t      st_size;
} Elf64_Sym;
```

Relocation Entry

- **Where** to write **what** value at load/link time
- For amd64:

```
typedef struct {
    Elf64_Addr r_offset;
    uint64_t   r_info;
    int64_t    r_addend;
} Elf64_Rela;
```

- r_info:
  - Relocation entry type
    - #define ELF64_R_TYPE(i) ((i) & 0xffffffff)
  - Associated symbol table entry index
    - #define ELF64_R_SYM(i) ((i) >> 32)
- amd64 ABI defines 37 relocation types
- gcc toolchain uses 13 types (1 not in ABI)

GOT and PLT

Global Offset Table and Procedure Linkage Table

- Each function requiring dynamic linking has an entry in each
- GOT is a table of addresses
- GOT[1] = object's link_map struct
  - Data on ELF objects used by RTLD/linker
- GOT[2] = &_dl_fixup (dynamic linker function)
- GOT entry for function is pointer to function or code in PLT that calls _dl_fixup
- PLT is code that works with GOT to run dynamic linker if needed

Dynamic section

- Table of metadata used by runtime loader

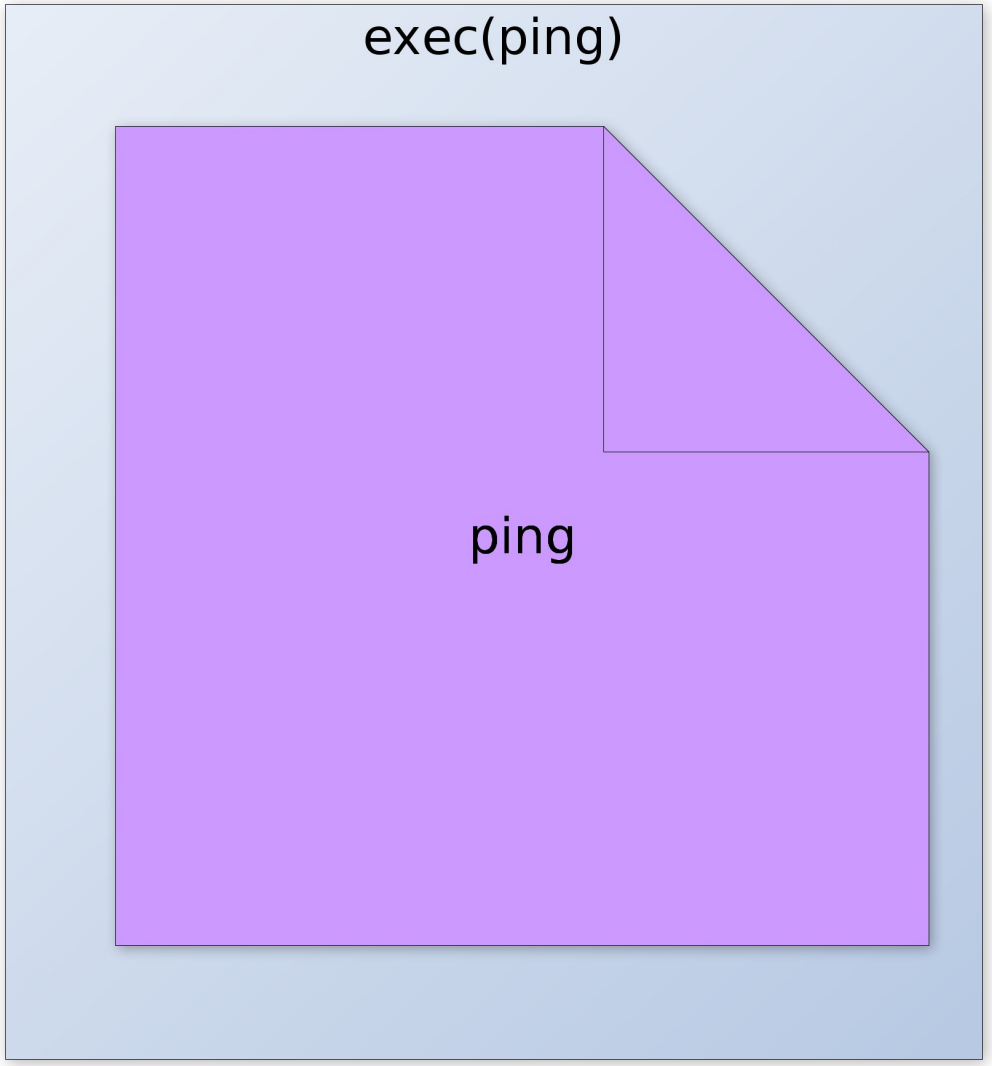
```
typedef struct {
    Elf64_Sxword    d_tag;
    union {
        Elf64_Xword d_val;
        Elf64_Addr  d_ptr;
    } d_un;
} Elf64_Dyn;
```

- Types of interest
  - **DT_RELA, DT_RELASZ**
  - DT_RELACOUNT
  - **DT_SYM**
  - DT_JMPREL, DT_PLTRELSZ

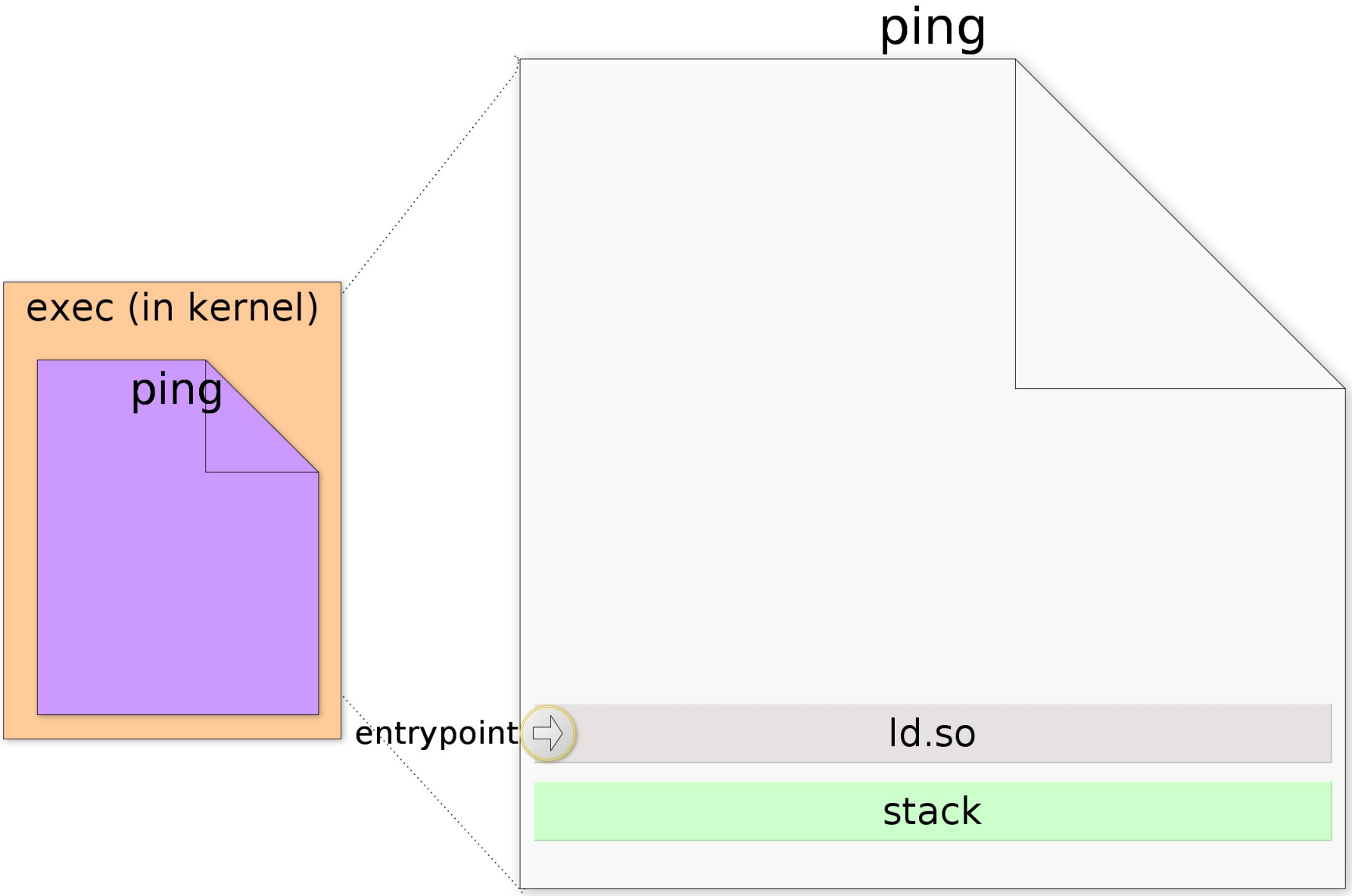
Interesting dynamic section entries

- DT_RELA, DT_RELASZ, DT_RELACOUNT
  - Start of .rela.dyn table, size, and number of entries of type R_*_RELATIVE
- DT_SYM
  - Location of symbol table (.dynsym)
- DT_JMPREL, DT_PLTRELSZ
  - Location of .rela.plt table
    - relocation entries processed by dynamic loader
  - Size of .rela.plt table

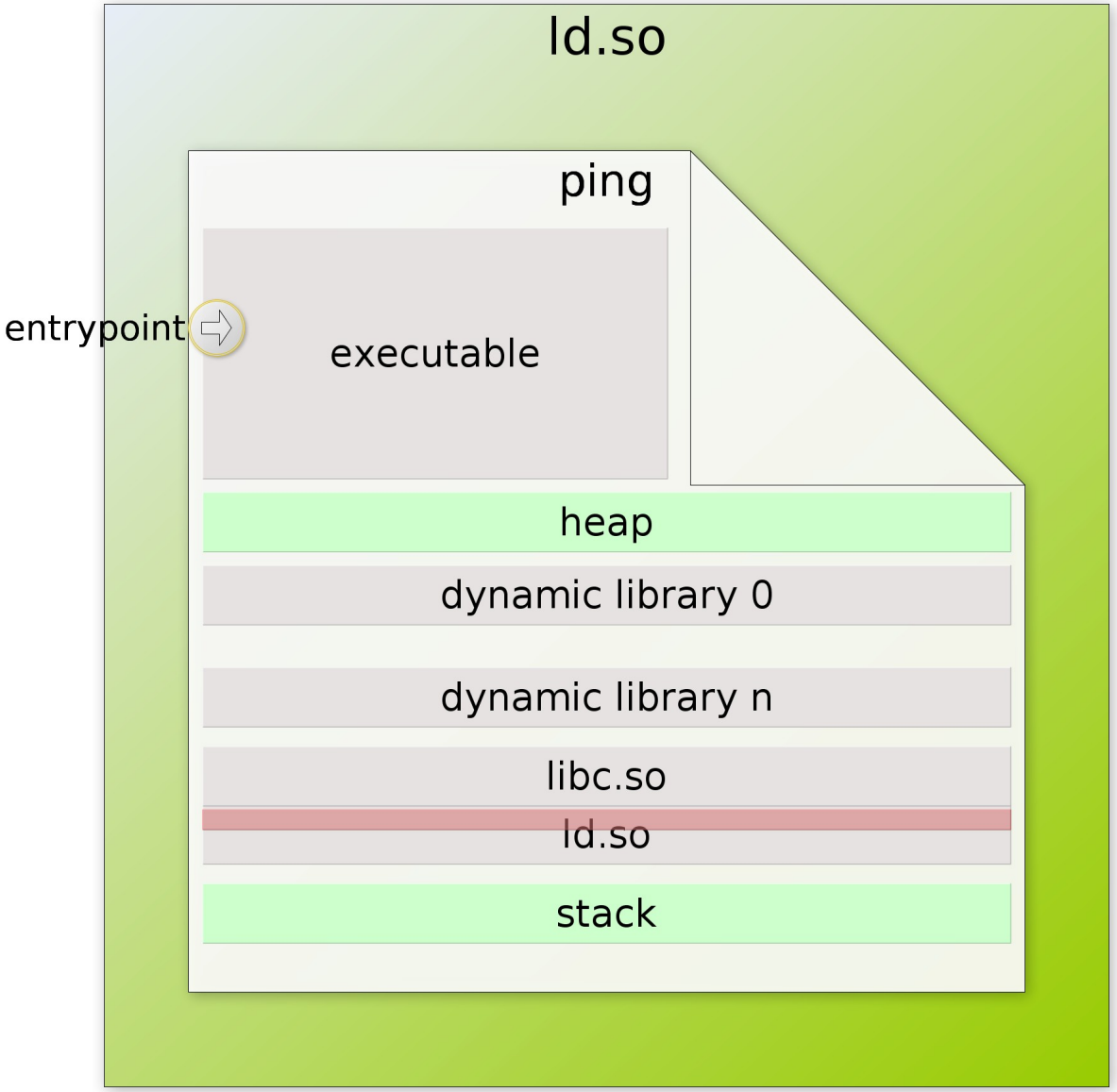
The story of exec



The story of exec



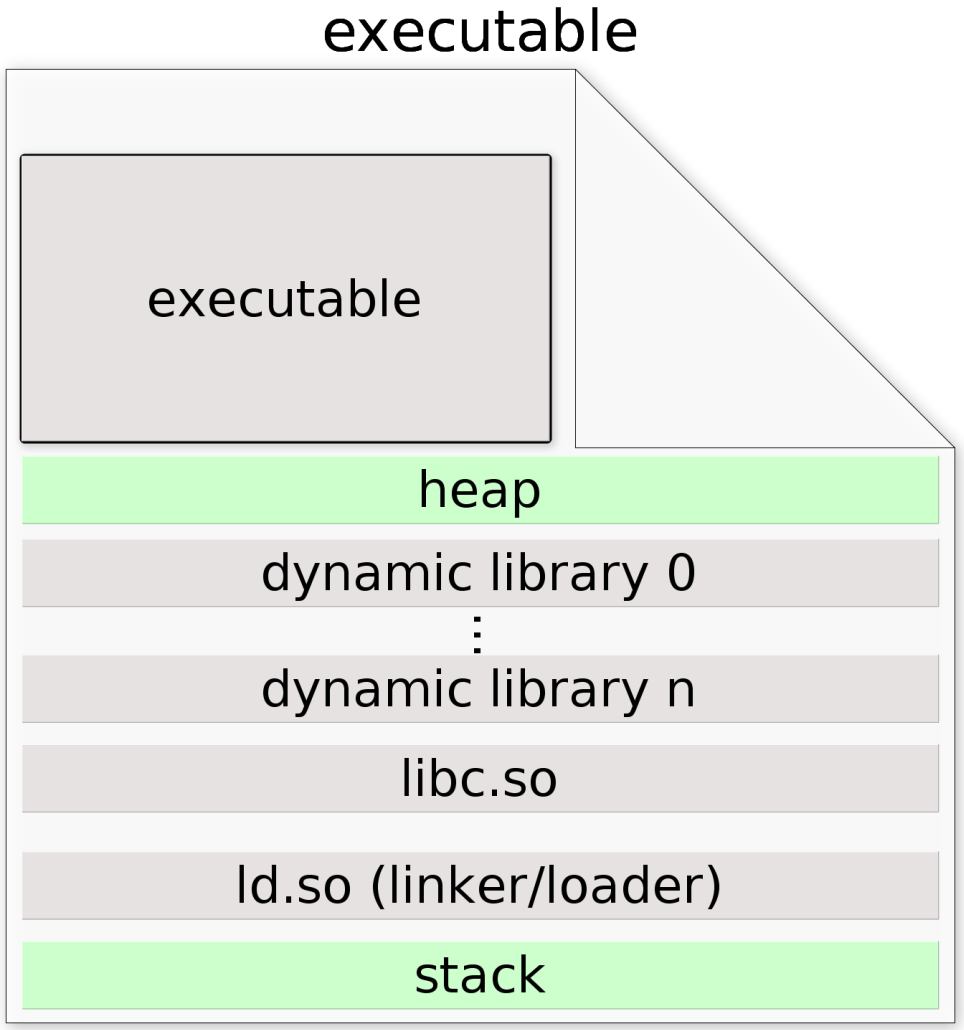
The story of exec



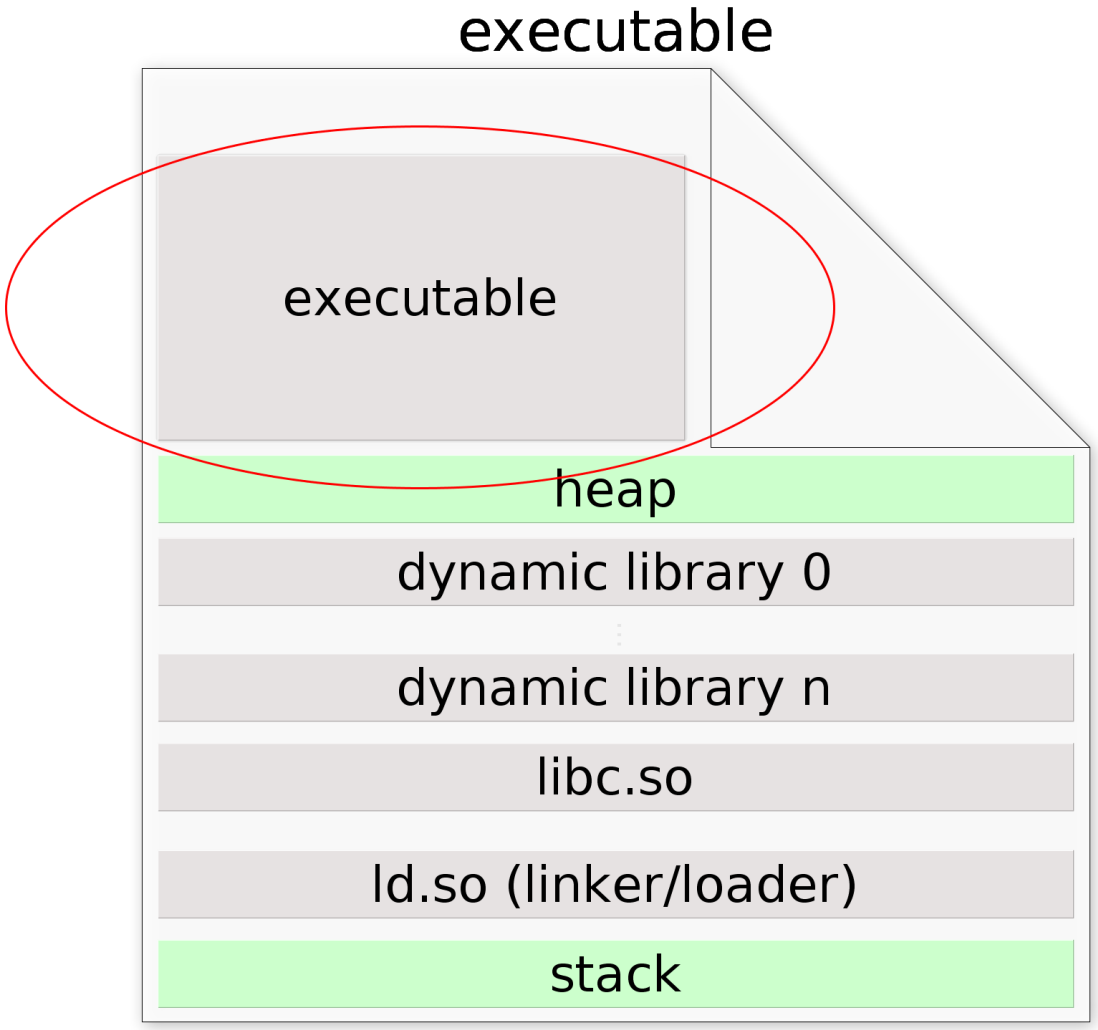
Memory layout of ping (abbrev)

- 00400000-00408000 r-xp ping
- 00607000-00608000 r--p ping
- 00608000-00609000 rw-p ping
- 00609000-0061c000 rw-p
- 02165000-02186000 rw-p [heap]
- 7fc2224d2000-7fc2224de000 r-xp libnss_files-2.13.so
- 7fc2226dd000-7fc2226de000 r--p libnss_files-2.13.so
- 7fc2226de000-7fc2226df000 rw-p libnss_files-2.13.so
- 7fc2226df000-7fc222876000 r-xp libc-2.13.so
- 7fc222a75000-7fc222a79000 r--p libc-2.13.so
- 7fc222a79000-7fc222a7a000 rw-p libc-2.13.so
- 7fc222a7a000-7fc222a80000 rw-p
- 7fc222a80000-7fc222aa1000 r-xp ld-2.13.so
- 7fc222c77000-7fc222c7a000 rw-p
- 7fc222c9d000-7fc222ca0000 rw-p
- 7fc222ca0000-7fc222ca1000 r--p ld-2.13.so
- 7fc222ca1000-7fc222ca3000 rw-p ld-2.13.so
- 7fff01379000-7fff0139a000 rw-p [stack]

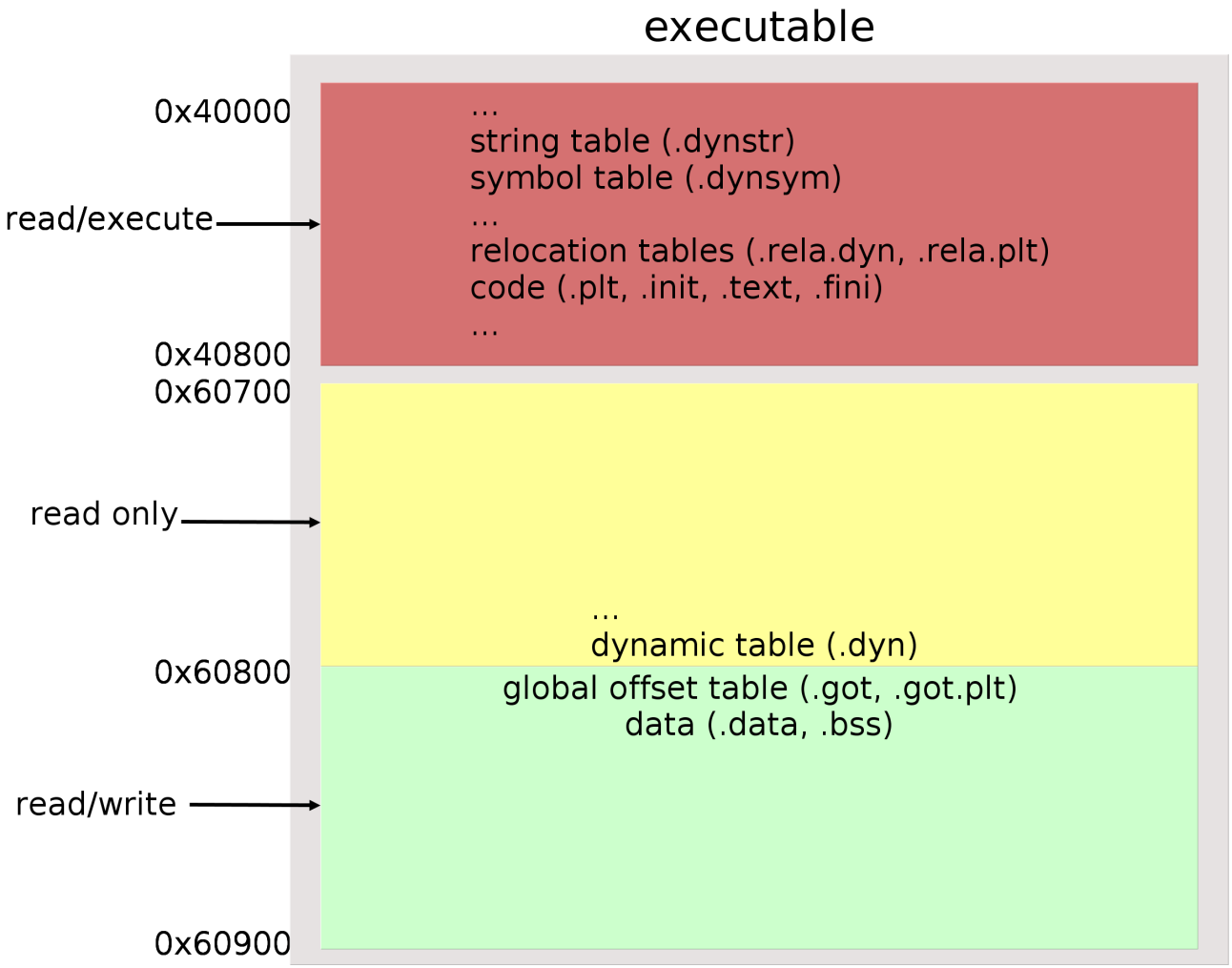
General process memory layout



General process memory layout

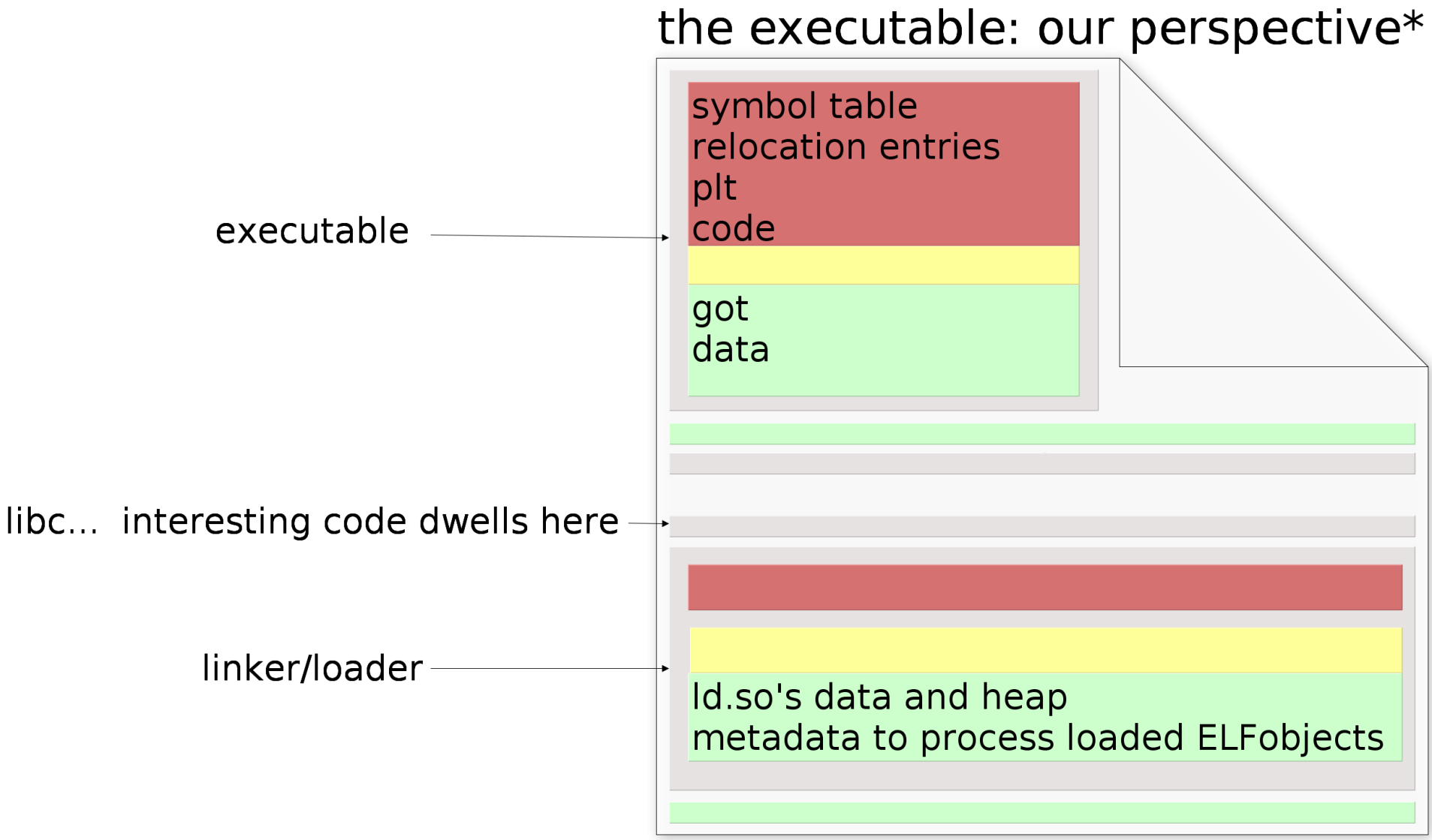


A processes' segments

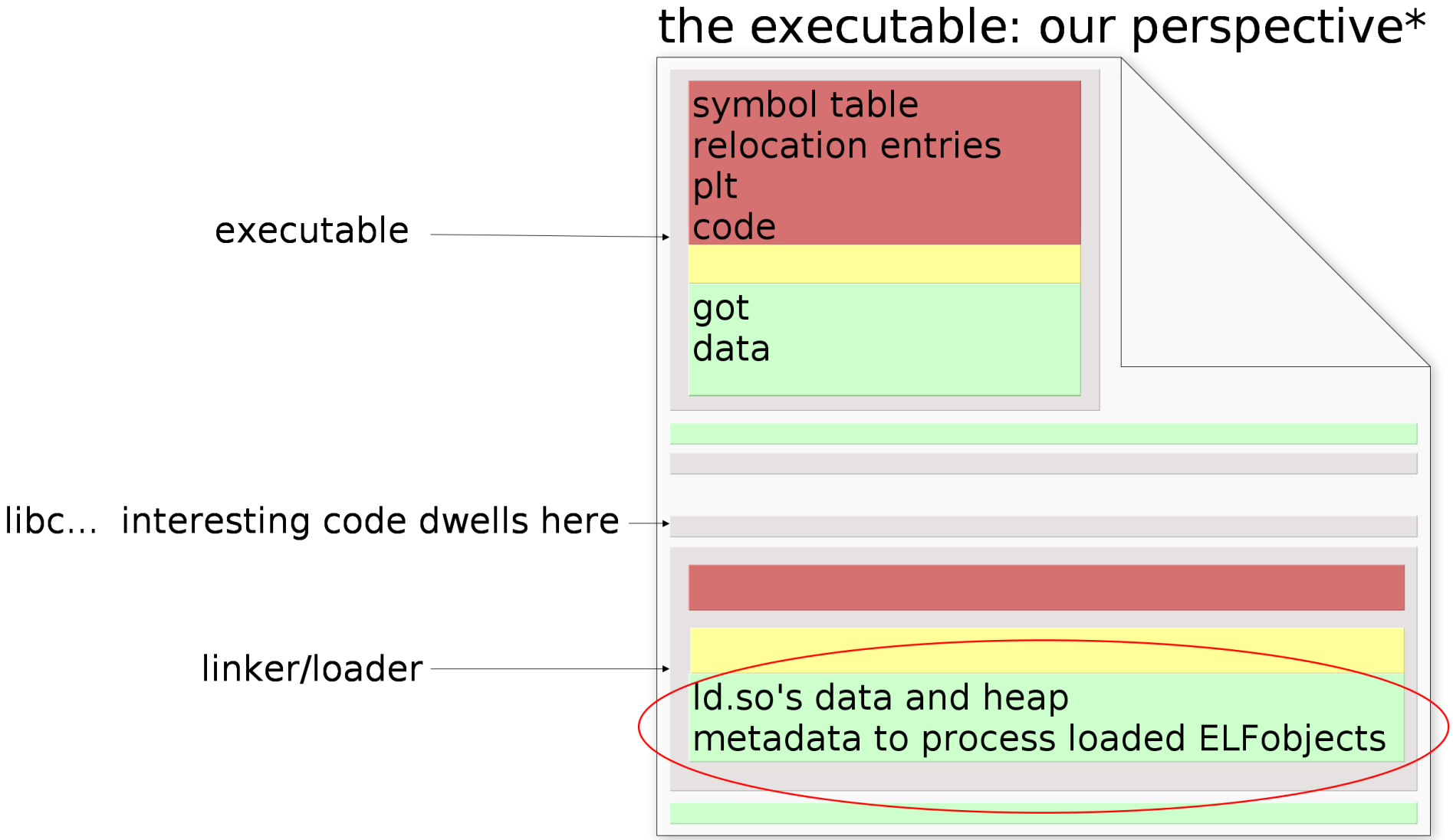



```
00400000-00408000 r-xp 00000000 08:06 261244    /bin/ping
00607000-00608000 r--p 00007000 08:06 261244    /bin/ping
00608000-00609000 rw-p 00008000 08:06 261244    /bin/ping
```

General process memory layout

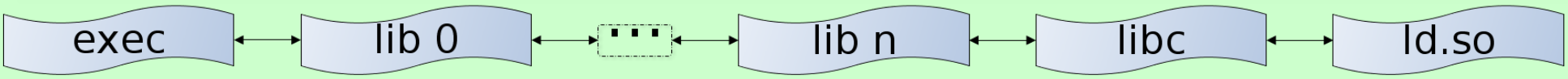


General process memory layout



ld.so link_map structures

```
struct link_map {
    ElfW(Addr) l_addr;          /* Base address shared object is loaded at.  */
    char *l_name;               /* Absolute file name object was found in.  */
    ElfW(Dyn) *l_ld;            /* Dynamic section of the shared object.  */
    struct link_map *l_next, *l_prev; /* Chain of loaded objects.  */
    ...
    struct libname_list *l_libname
    ...
    ElfW(Dyn) *l_info[DT_NUM + DT_THISPROCNUM + DT_VERSIONTAGNUM
    ...
    union {
      const Elf32_Word *l_gnu_chain_zero;
      const Elf_Symndx *l_buckets;
    };
    unsigned int l_direct_opencount; /* Reference count for dlopen/dlclose.  */
    enum    {                   /* Where this object came from.  */
       lt_executable,           /* The main executable program.  */
       lt_library,              /* Library needed by main executable.  */
       lt_loaded                /* Extra run-time loaded shared object.  */
      } l_type:2;
    unsigned int l_relocated:1; /* Nonzero if object's relocations done.  */
    ...
    size_t l_relro_size;
    ...
};
```



Fun ways to abuse ELF metadata

- Change entrypoint to point to injected code
- Inject object files (**mayhem, phrack 61:8**)
- Intercept library calls to run injected code
  - Injected in executable
    - Cesare PLT redirection (**Phrack 56:7**)
    - Mayhem ALTPLT (Phrack 61:8)
  - Resident in attacker-built library
    - LD_PRELOAD (example: **Jynx-Kit** rootkit)
    - DT_NEEDED (Phrack 61:8)
    - Loaded at runtime (**Cheating the ELF**, the **grugq**)
  - Injected in library
- LOCREATE (Skape, Uniformed 2007)
  - Unpack binaries using relocation entries

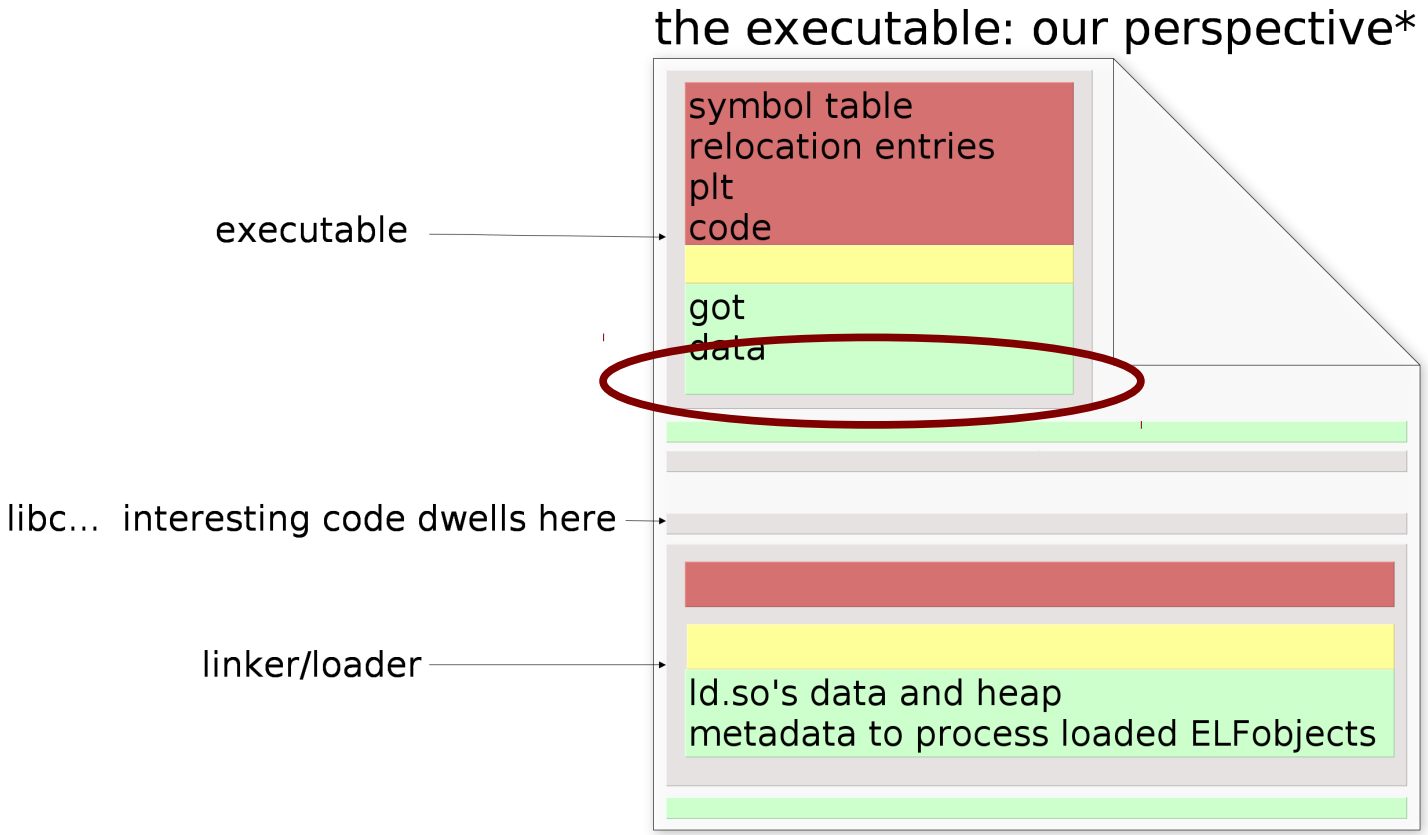
More fun with relocation entries

Warning. The following you are about to see is architecture and libc implementation dependant. Please try this at home, but there are no guarantees it will work with your architecture/gcc toolchain combination.
(Ours is Ubuntu 11.10's eglibc-2.13 on amd64)

Not all Brainfuck instructions work with ASLR.

Injecting Relocation/Symbol tables

- Use eresi toolkit
- Injects into executable's r/w segment



Relocation Entry Type Primer

```
typedef struct {
    Elf64_Addr r_offset;
    uint64_t   r_info; // contains type and symbol number
    int64_t    r_addend;
} Elf64_Rela;
```

- Let r be our Elf64_Rela, s be the corresponding Elf64_Sym (if applicable)
- R_X86_64_COPY
  - memcpy(r.r_offset, s.st_value, s.st_size)
- R_X86_64_64
  - *(base+r.r_offset) = s.st_value +r.r_addend+base
- R_X86_64_32
  - Same as _64, but only writes 4 bytes
- R_X86_64_RELATIVE
  - *(base+r.r_offset = r.r_addend+base)

Relocation & STT_IFUNC symbols

- Symbols of type STT_IFUNC are special!
- st_value treated as a function pointer

```
#include <stdio.h>
int foo (void) __attribute__ ((ifunc ("foo_ifunc")));
static int global = 1;
static int f1 (void) { return 0; }
static int f2 (void){ return 1; }
void *foo_ifunc (void) { return global == 1 ? f1 : f2; }
int main () { printf ("%d\n", foo()); }
```

Symbols:

```
43: 0000000000400524   11 FUNC    LOCAL  DEFAULT    13 f1
44: 000000000040052f   11 FUNC    LOCAL  DEFAULT    13 f2
57: 000000000040053a   29 FUNC    GLOBAL DEFAULT    13 foo_ifunc
62: 000000000040053a   29 IFUNC   GLOBAL DEFAULT    13 foo
```

```
000000000040053a <foo_ifunc>:
  ....
  40053e:       8b 05 e4 0a 20 00       mov    0x200ae4(%rip),%eax        # 601028 <global>
  400544:       83 f8 01                cmp    $0x1,%eax
  400547:       75 07                   jne    400550 <foo_ifunc+0x16>
   ....
  400550:       b8 2f 05 40 00          mov    $0x40052f,%eax
  400555:       5d                      pop    %rbp
  400556:       c3                      retq
```

Brainfuck Primer

- 6 instructions:
  - **1) >** Increment the pointer.
  - 2) **<** Decrement the pointer.
  - **3) +** Increment the byte at the pointer.
  - 4) **-** Decrement the byte at the pointer.
  - **5) [** Jump forward past the matching] if the byte at the pointer is zero.
  - **6)]** Jump backward to the matching [unless the byte at the pointer is zero.
  - 7) **.** Output the byte at the pointer.
  - 8) **,** Input a byte and stor in byte at the pointer.

Source: http://www.muppetlabs.com/~breadbox/bf/

Brainfuck Primer

- 6 instructions:
  1) **>** Increment the pointer.
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  7) **.** Output the byte at the pointer.
  8) **,** Input a byte and stor in byte at the pointer.

Source: http://www.muppetlabs.com/~breadbox/bf/

Brainfuck Primer
Hello, World

```
// Hello World in brainfuck
// Creds to Speedy
>++++++++++[<+++++++++>-]<.>+++++++
[<++++>-]<+.+++++++..+++.[-]
>++++++++[<++++>-] <.>++++++++++++
[<+++++++++>-]<-.--------.+++
.------.--------.[-]>++++++++[<++++>- ]<+.[-]
++++++++++.
```

Source: www.helloworld.org

ELF Brainfuck Setup

.dynsym table

(empty)
Original dynsym 0
Original dynsym 1
...
Original dynsym n
Address tape head is pointing at
Copy of tape head's value
IFUNC that always returns 0
Copy of IFUNC address

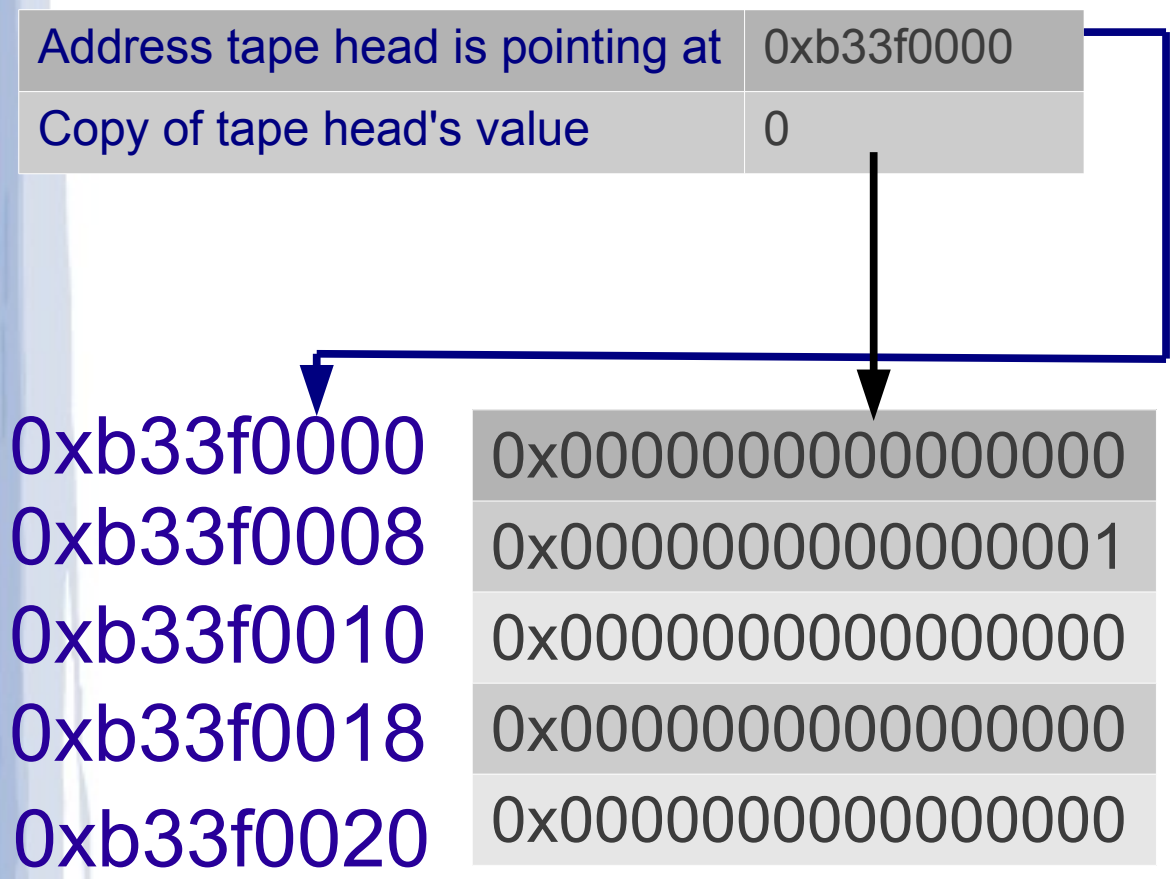
.rela.dyn table

Brainfuck instruction 0
...
Brainfuck instruction n
”Code” that cleans up some link_map data
”Code” that forces branch to next reloc entry
”Code” that finishes cleaning link_map
Original .rela.dyn entry 0
...
Original .rela.dyn entry m

ELF Brainfuck Setup

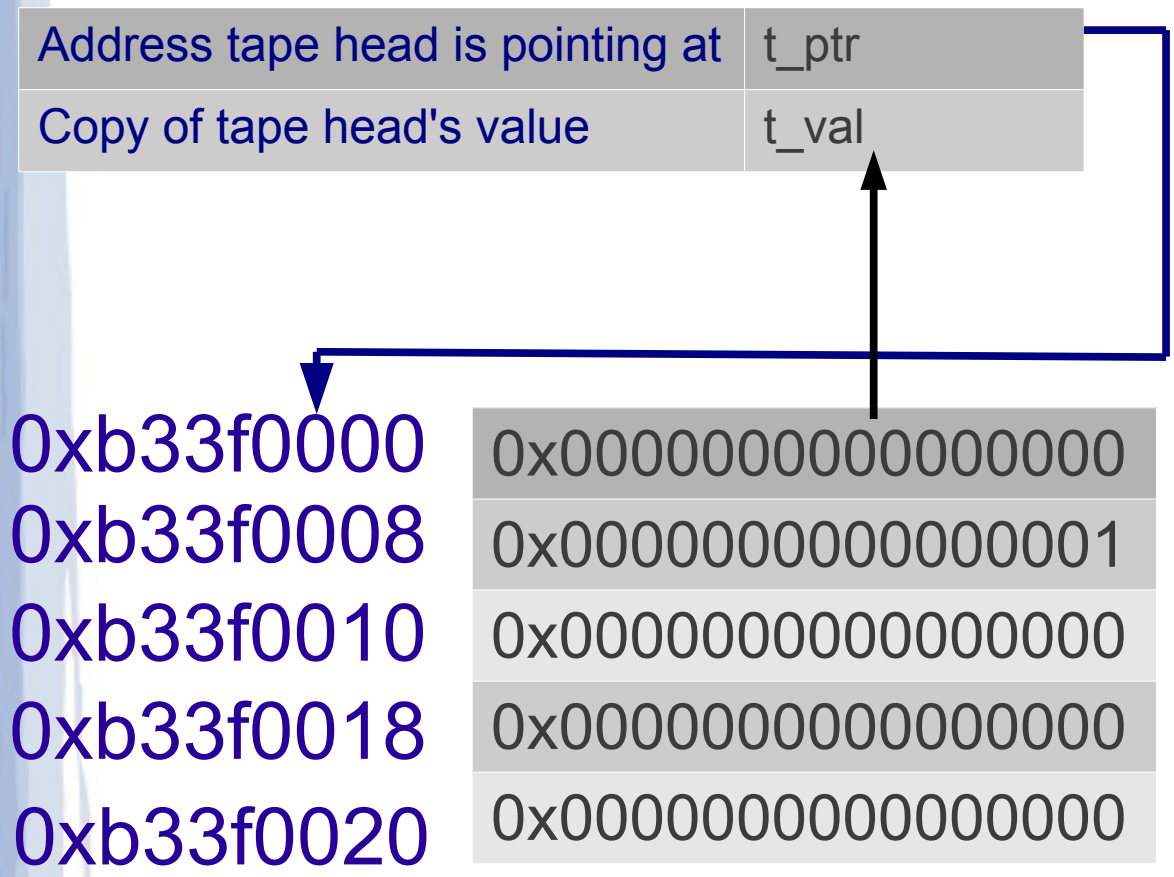
- Data needed at compile time
  - Address of executable's link_map
    - In future versions, get this automatically
  - Address of instructions that return 0
    - ROP-style
  - Stack location
  - Location in memory of executable's:
    - DT_RELA
    - DT_RELASZ
    - DT_SYM
    - DT_JMPREL
    - DT_PLTRELSZ
    - Collected at runtime (compile time?)
- Compiler works with existing executable

ELF Brainfuck Tape Pointer



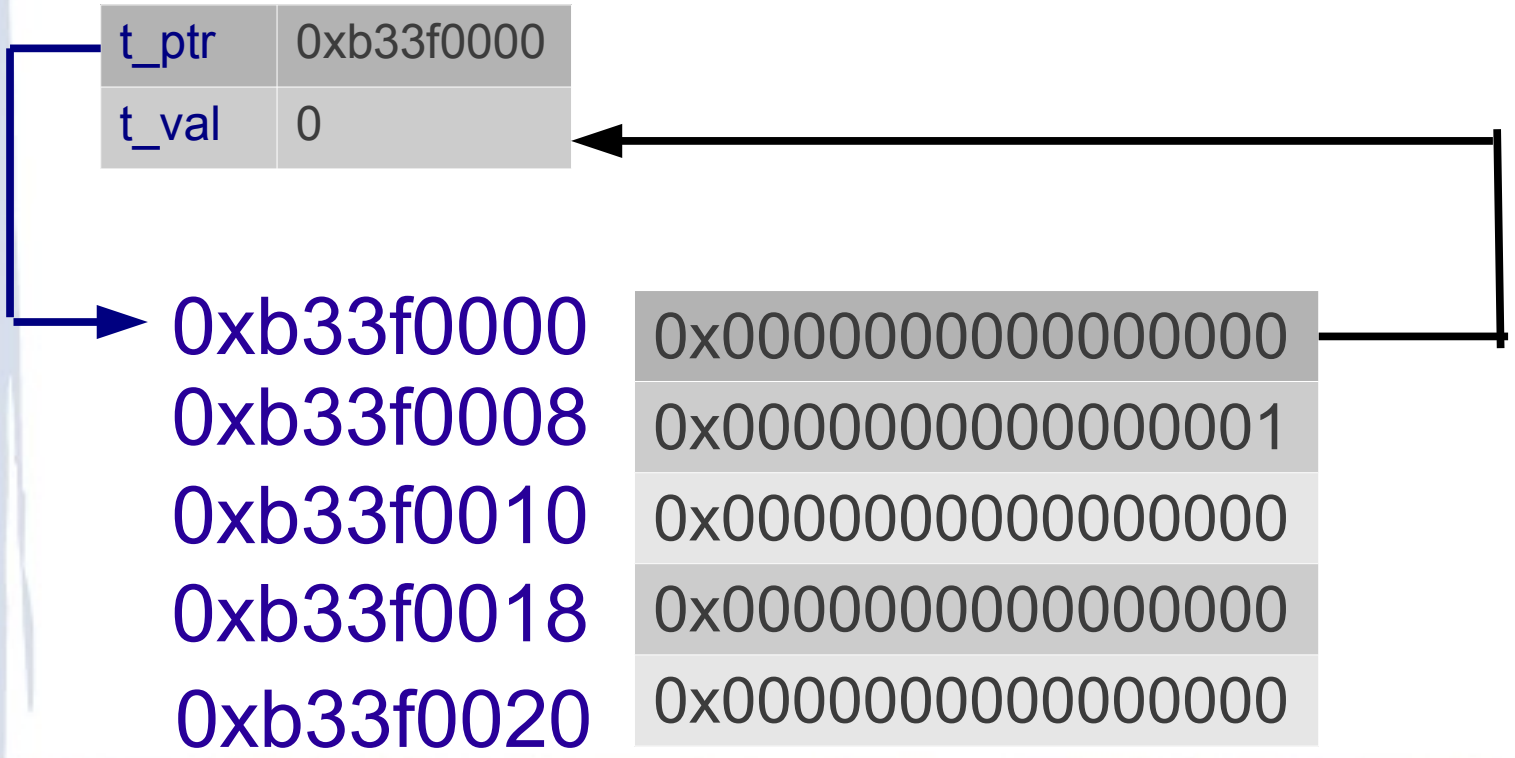
- Relocation/symbol entries must be in writable memory
- Tape must be in writable memory

ELF Brainfuck Tape Pointer



ELF Brainfuck Tape Pointer

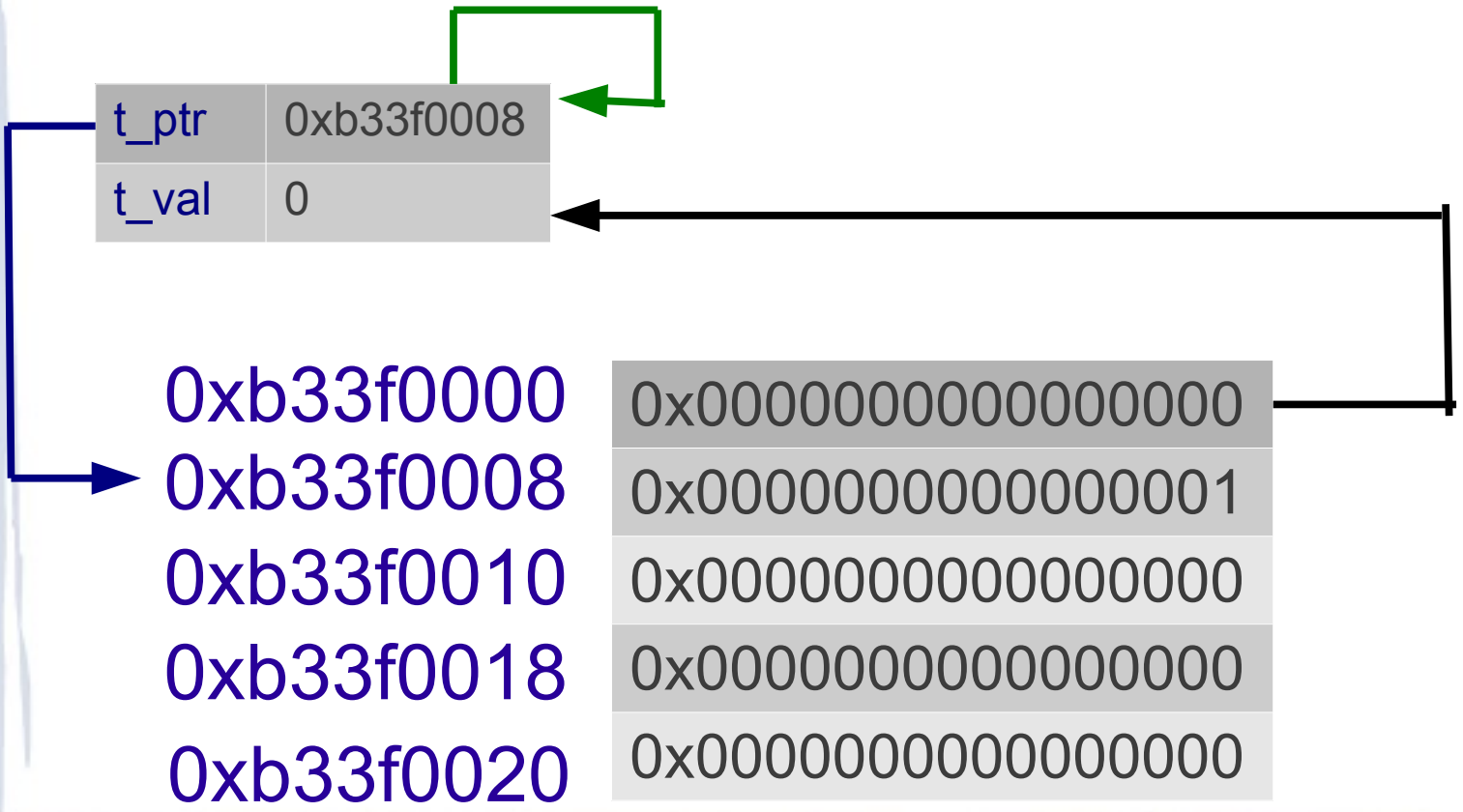
mv_ptr = {offset=&(t_ptr.value), type = 64, sym=t_ptr, addend=8*n}
copy_val = {offset=&(t_val.value), type = COPY, sym=p_tptr}



ELF Brainfuck Tape Pointer

n=1

mv_ptr = {offset=&(t_ptr.value), type = 64, sym=t_ptr, addend=8}
copy_val = {offset=&(t_val.value), type = COPY, sym=p_tptr}

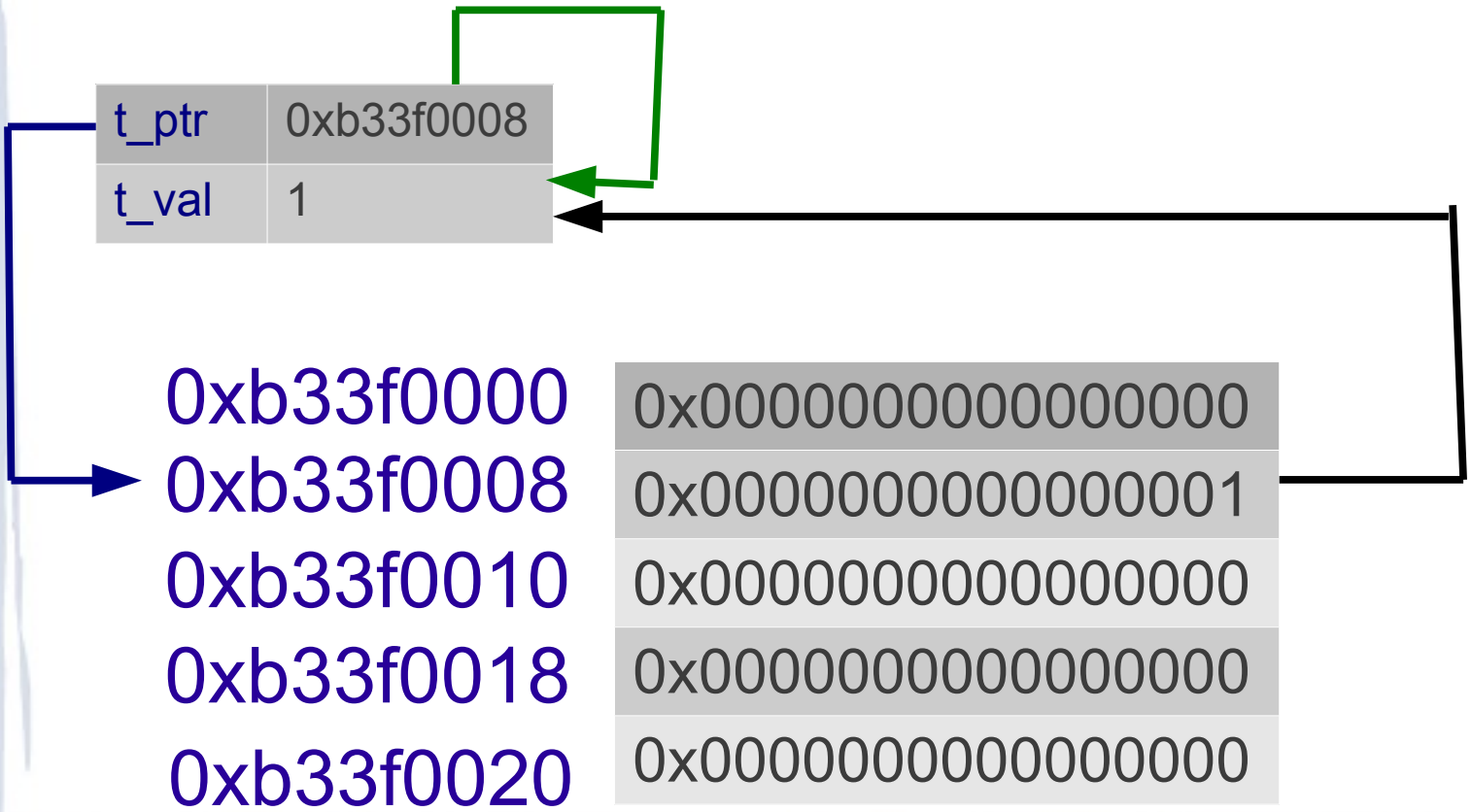


ELF Brainfuck Tape Pointer

n=1

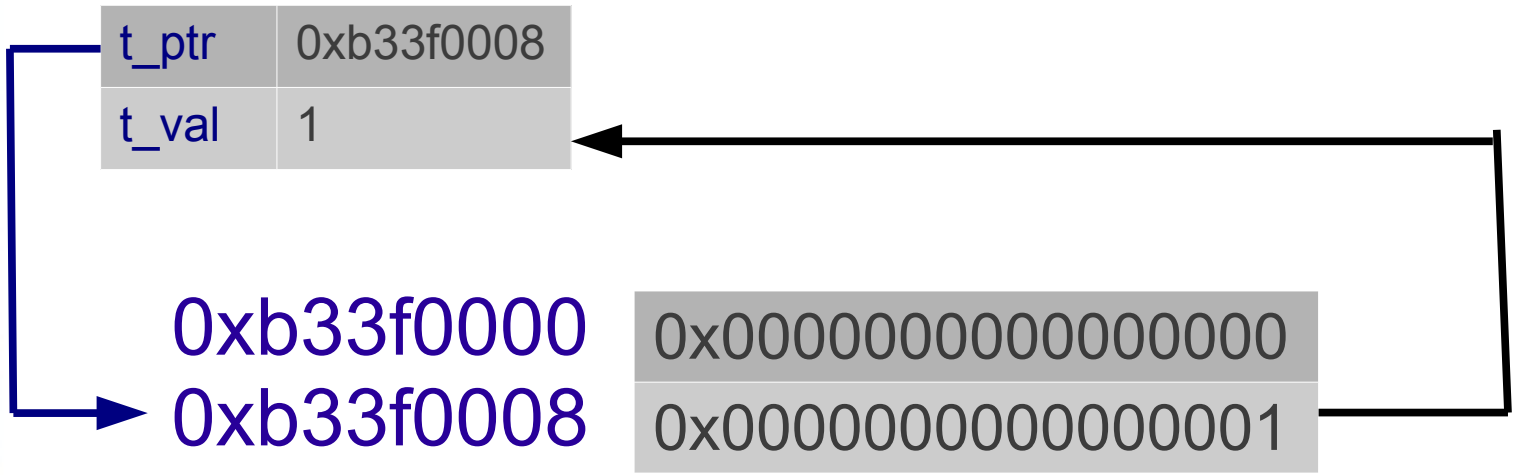
mv_ptr = {offset=&(t_ptr.value), type = 64, sym=t_ptr, addend=8}

copy_val = {offset=&(t_val.value), type = COPY, sym=p_tptr}



ELF Brainfuck Tape Inc/Dec

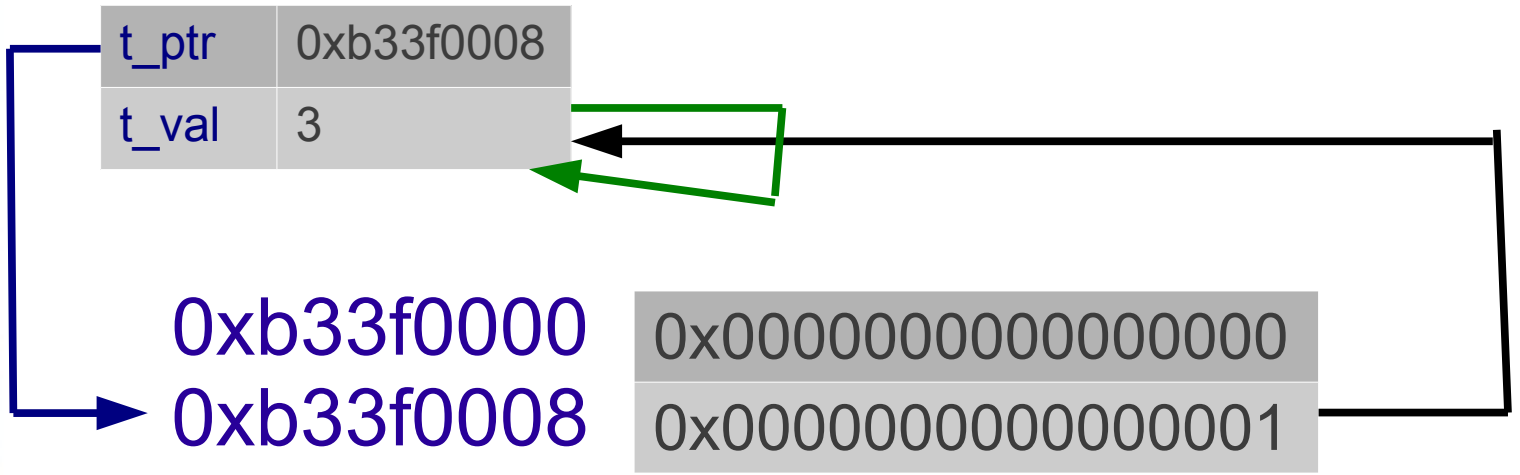
add = {offset=&(t_ptr.value), type = 64, sym=t_val, addend=n}
get_ptr = {offset=&(update.offset), type = 64, sym=t_ptr}
update = {offset=**????**, type = 64, sym=t_val}



ELF Brainfuck Tape Inc/Dec

n=2

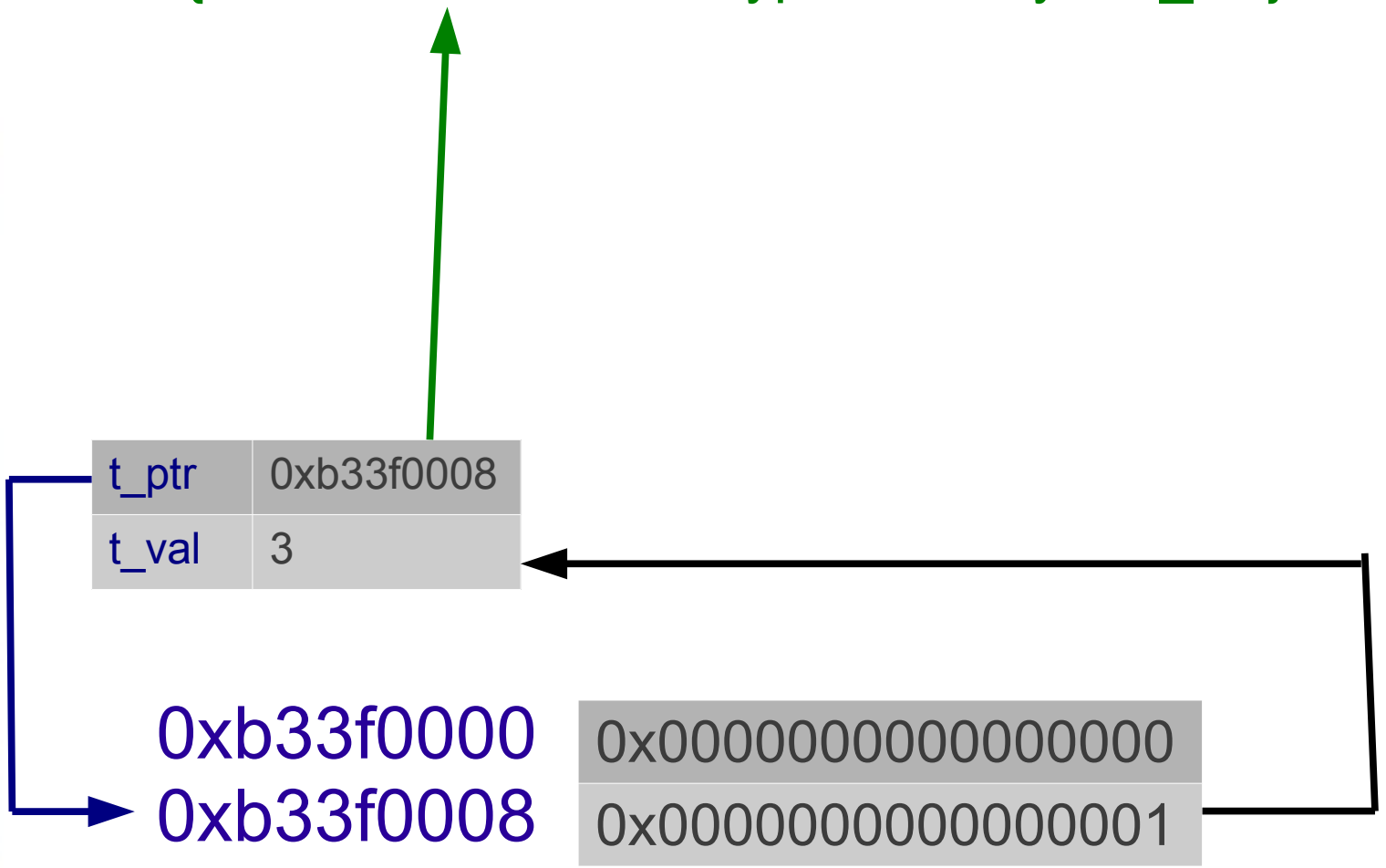
add = {offset=&(t_ptr.value), type = 64, sym=t_val, addend=2}
get_ptr = {offset=&(update.offset), type = 64, sym=t_ptr}
update = {offset=**????**, type = 64, sym=t_val}



ELF Brainfuck Tape Inc/Dec

n=2

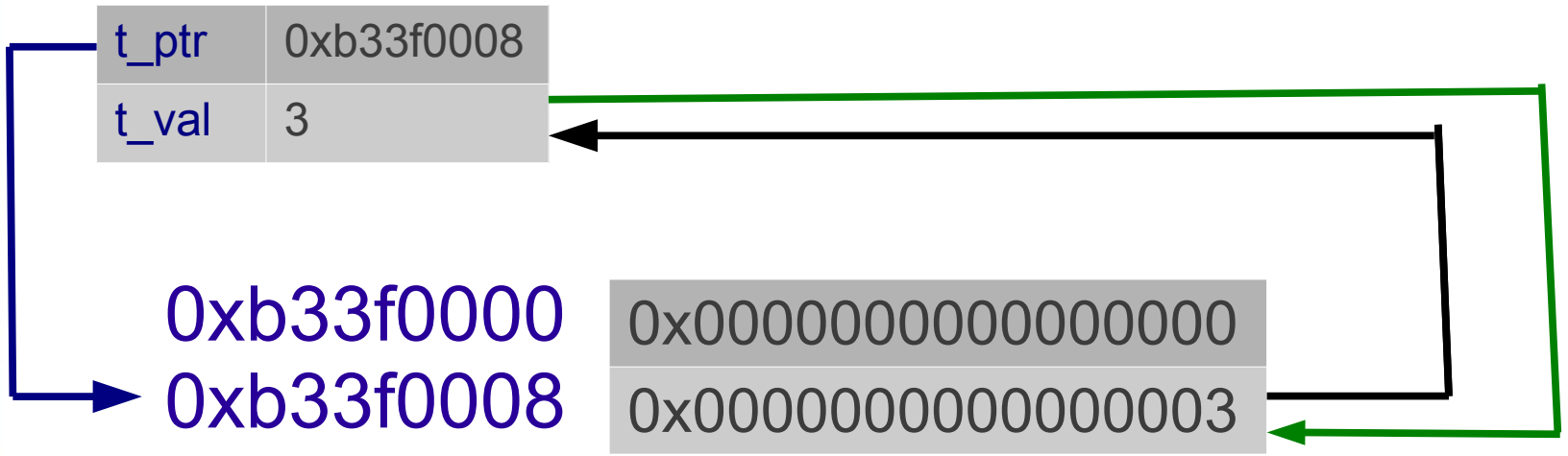
add = {offset=&(t_ptr.value), type = 64, sym=t_val, addend=2}
get_ptr = {offset=&(update.offset), type = 64, sym=t_ptr}
update = {offset=**0xb33f0008**, type = 64, sym=t_val}



ELF Brainfuck Tape Inc/Dec

n=2

add = {offset=&(t_ptr.value), type = 64, sym=t_val, addend=2}
get_ptr = {offset=&(update.offset), type = 64, sym=t_ptr}
update = {offset=0xb33f0008, type = 64, sym=t_val}



ELF BF Unconditional Branch/Loop

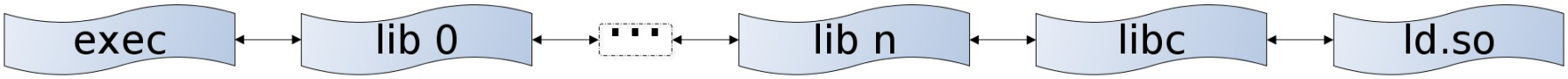
- How relocation entries get processed

```
do
 {
   struct libname_list *lnp = l->l_libname->next;

   while (__builtin_expect (lnp != NULL, 0))
     {
       lnp->dont_free = 1;
       lnp = lnp->next;
     }

   if (l != &GL(dl_rtld_map))
     _dl_relocate_object (l, l->l_scope, GLRO(dl_lazy) ? RTLD_LAZY : 0,
                          consider_profiling);
   ...
   l = l->l_prev;
 }
```

TODO:
- set l->l_prev = l



ELF Brainfuck Unconditional Branch

- How relocation entries get processed

```
do
 {
   struct libname_list *lnp = l->l_libname->next;

   while (__builtin_expect (lnp != NULL, 0))
     {
       lnp->dont_free = 1;
       lnp = lnp->next;
     }

   if (l != &GL(dl_rtld_map))
     _dl_relocate_object (l, l->l_scope, GLRO(dl_lazy) ? RTLD_LAZY : 0,
                          consider_profiling);
   ...
   l = l->l_prev;
 }
while (l);
```

TODO:
- set l->l_prev = l

ELF Brainfuck Unconditional Branch

- How relocation entries get processed

```
void
_dl_relocate_object (struct link_map *l, struct r_scope_elem *scope[],
                     int reloc_mode, int consider_profiling)
{

  if (l->l_relocated)
    return;
  …
    ELF_DYNAMIC_RELOCATE (l, lazy, consider_profiling);
  …
  /* Mark the object so we know this work has been done.  */
  l->l_relocated = 1;
  ...
  /* In case we can protect the data now that the relocations are
     done, do it.  */
  if (l->l_relro_size != 0)
    _dl_protect_relro (l);
  ...
}
```

TODO:
- set l->l_prev = l
- fix l->l_relocated

ELF Brainfuck Unconditional Branch

- How relocation entries get processed

```
void
_dl_relocate_object (struct link_map *l, struct r_scope_elem *scope[],
                     int reloc_mode, int consider_profiling)
{

  if (l->l_relocated)
    return;
  …
    ELF_DYNAMIC_RELOCATE (l, lazy, consider_profiling);
  …
  /* Mark the object so we know this work has been done.  */
  l->l_relocated = 1;
  ...
  /* In case we can protect the data now that the relocations are
     done, do it.  */
  if (l->l_relro_size != 0)
    _dl_protect_relro (l);
  ...
}
```

TODO:
- set l->l_prev = l
- fix l->l_relocated
- set l->l_relro_size = 0

ELF Brainfuck Unconditional Branch

- How relocation entries get processed

```
do
 {
  struct libname_list *lnp = l->l_libname->next;

  while (__builtin_expect (lnp != NULL, 0))
   {
    lnp->dont_free = 1;
    lnp = lnp->next;
   }

  if (l != &GL(dl_rtld_map))
    _dl_relocate_object (l, l->l_scope, GLRO(dl_lazy) ? RTLD_LAZY : 0,
                         consider_profiling);
  ...
  l = l->l_prev;
 }
while (l);
```

TODO:
- set l->l_prev = l
- fix l->l_relocated
- set l->l_relro_size = 0

ELF Brainfuck Unconditional Branch Bookeeping

- Fix l->l_relocated
- Set l->l_prev = l
- Set l->l_relro_size = 0
- Set l->l_info[DT_RELA] = &next rel to process
- Fix l->l_info[DT_RELASZ]

ELF Brainfuck Unconditional Branch Bookeeping

- Fix l->l_relocated
  - {offset =&(l->l_buckets), type = RELATIVE, addend=0}
  - {offset =&(l->l_direct_opencount), type = RELATIVE, addend=0}
  - {offset =&(l->l_libname->next), type = RELATIVE, addend=&(l->l_relocated) + 4*sizeof(int)}
- Set l->l_prev = l
  - {offset =&(l->l_prev), type = RELATIVE, addend=&l}
- Set l->l_relro_size = 0
  - (etc)
- Set l->l_info[DT_RELA] = &next rel to process
- Fix l->l_info[DT_RELASZ]

ELF Brainfuck Unconditional Branch Skip remaining relocation entries

```
for (; r < end; ++r)
  {
    ElfW(Half) ndx = version[ELFW(R_SYM) (r->r_info)] & 0x7fff;
    elf_machine_rel (map, r, &symtab[ELFW(R_SYM) (r->r_info)],
                     &map->l_versions[ndx],
                     (void *) (l_addr + r->r_offset));
  }
```

- end is on stack, set it to 0

{offset =&end, type = RELATIVE, addend=0}

ELF Brainfuck Conditional Branches

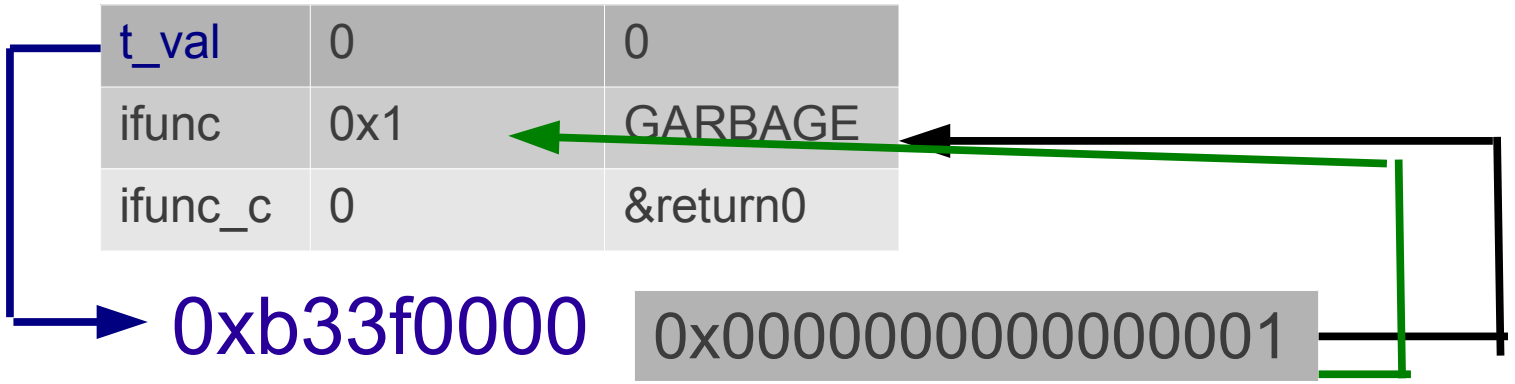
- Perform all branch book keeping
- IFUNC symbol only processed as function if st_shndx != 0

.dynsym table

(empty)
Original dynsym 0
Original dynsym 1
...
Original dynsym n
Address tape head is pointing at
Copy of tape head's value
IFUNC that always returns 0
Copy of IFUNC address

ELF Brainfuck Conditional Branches

setifunc = {offset=&(ifunc.shndx), type = 32, sym=t_val}*
get_ptr = {offset=&(ifunc.value), type = 32, sym=ifunc_c}
update = {offset=&end, type = 64, sym=ifunc}



*BUG ALERT: A symbol's st_shndx is only 2 bytes long. Tape entries need to be 2 bytes long or less for this to behave as expected. This will be fixed in future versions of the bf compiler.

ELF Brainfuck Conditional Branches

setifunc = {offset=&(ifunc.shndx), type = 32, sym=t_val}
get_ptr = {offset=&(ifunc.value), type = 32, sym=ifunc_c}
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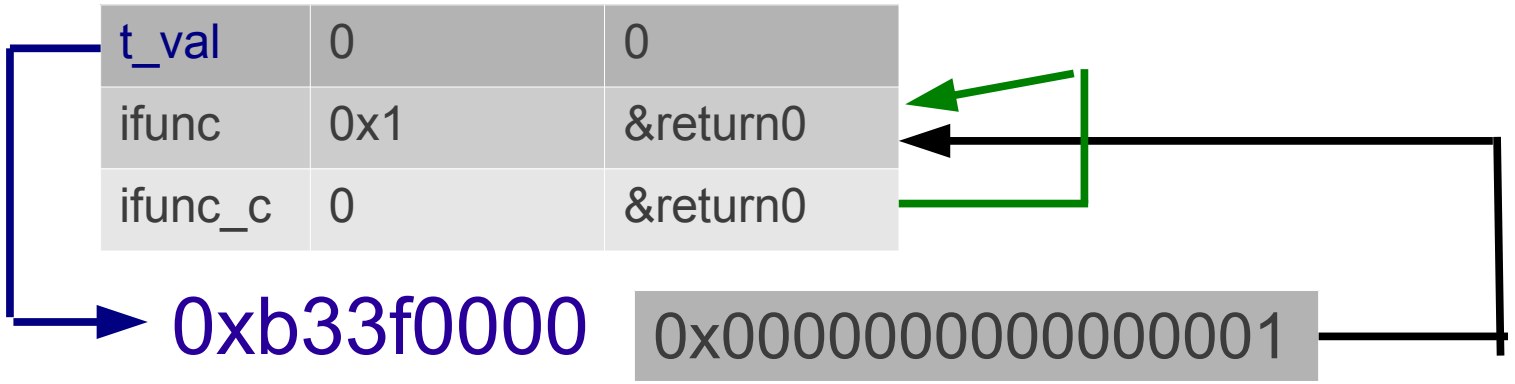

ELF Brainfuck Conditional Branches

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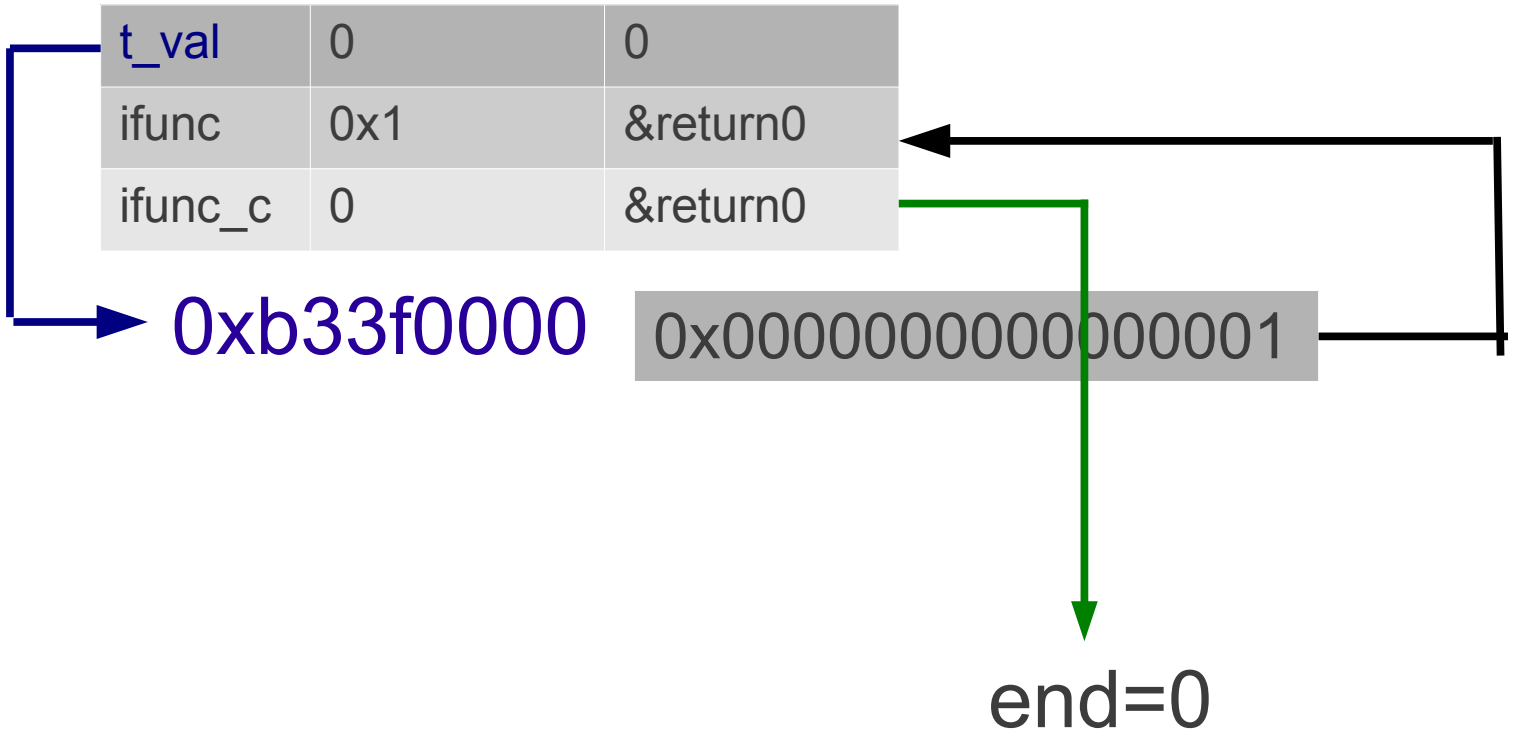

ELF Brainfuck Conditional Branches

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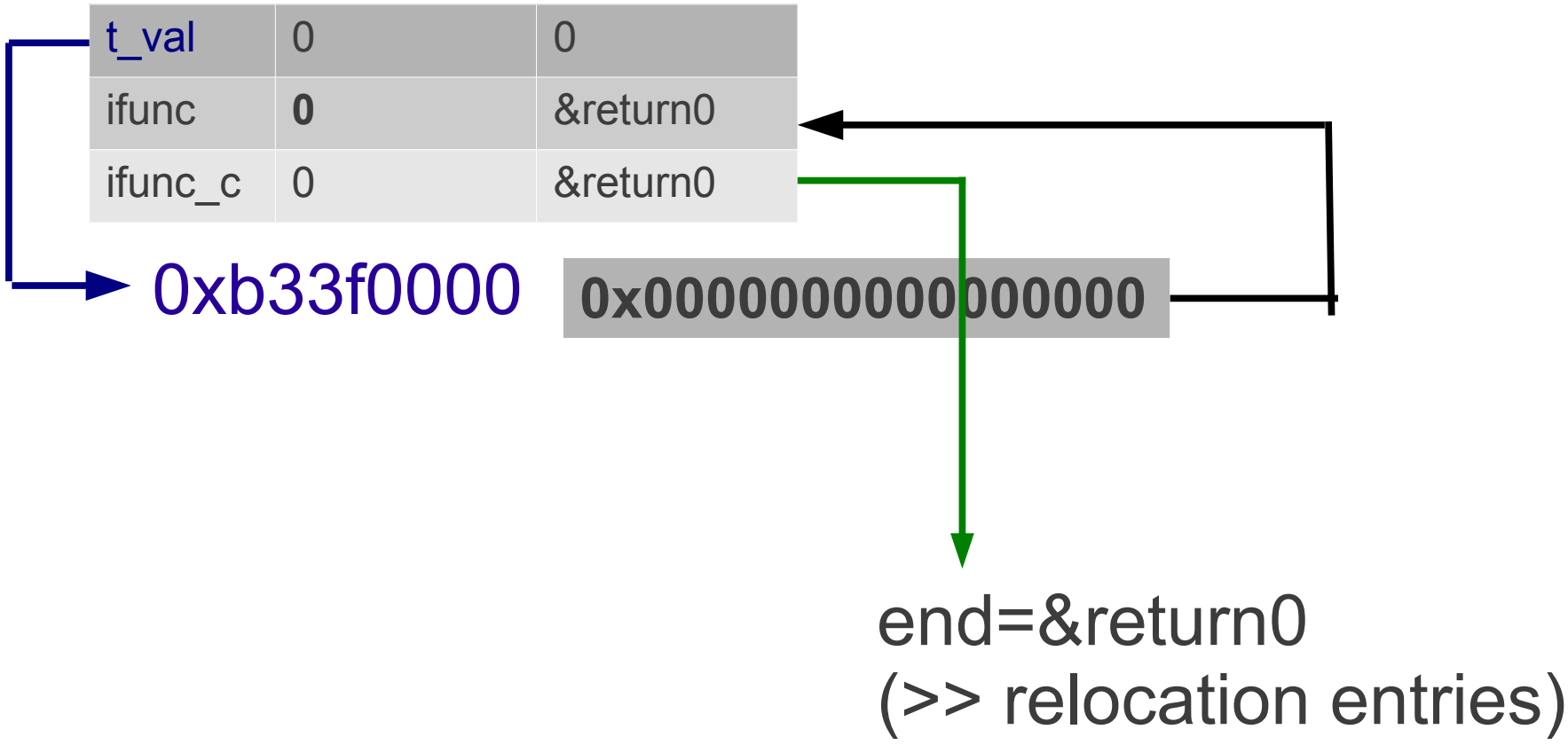


ELF Brainfuck '['

- ”Jump forward past the matching] if the byte at the pointer is zero”
- Prepare for branch, set branch location to & of entry after unconditional branch
- If value == 0, run uncondtional branch:
  - Branch past ']'
- If value != zero
  - We have skipped over unconditional branch
  - Continue to process relocation entries after '['

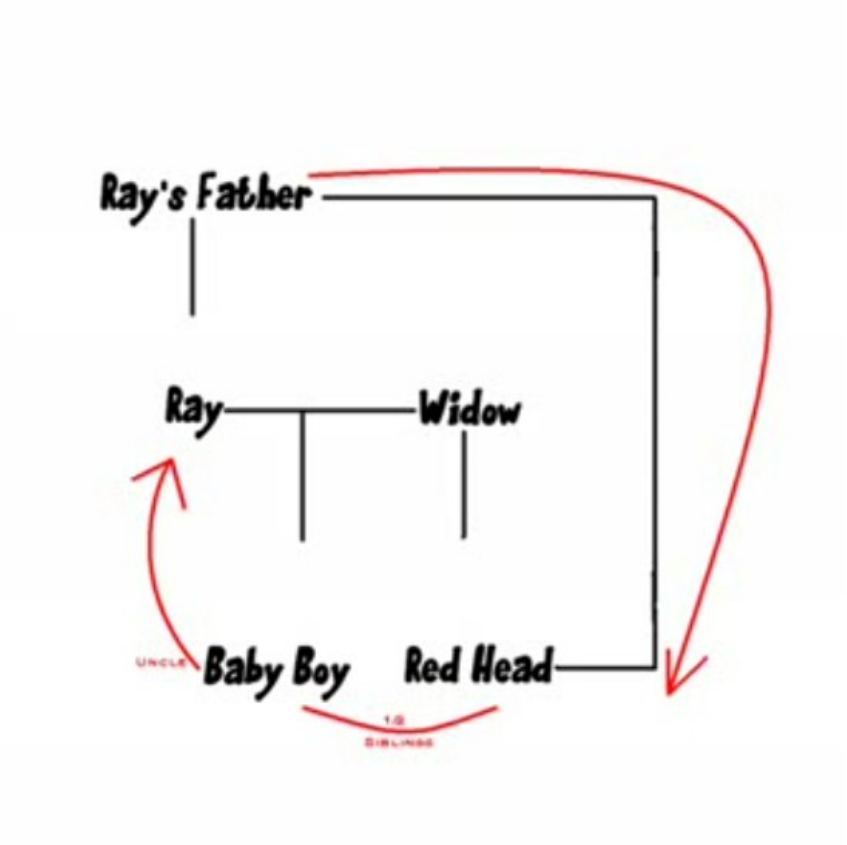
ELF Brainfuck ']'

- ”Jump backward to the matching [unless the byte at the pointer is 0”
- Prepare for branch, set branch location to & of relocation entry after '['
- If value == 0, continues processing
- If value != zero
  - Stops processing relocaiton entries, branch executes

Implementation Notes

- Used eresi toolchain to inject/edit metadata
- Injects metadata into r/w section
- More bookkeeping is necessary to ensure executable works (not mentioned in talk)
- Code coming soon to a github near you
  - 30.May.2012
  - elf-bf-tools repository on github

More fun with relocation entries: I'm My Own Grandpa



Following a pointer

- To get linkmap->l_next->l_addr:
- Store &got+0x8 in a symbol (DT_PLTGOT value)

Symbols:

symgot = {value:**&got+8**, size: **8**, **...**}

- Use the following relocation entries with that symbol

Relocation entries:

get_exec_linkmap = {offset=&(symgot.value), type = COPY, sym=0}
get_l_next = {offset=&(symgot.value), type = 64, sym=0, addend=0x18}
deref_l_next = {offset=&(symgot.value), type = COPY, sym=0}
get_l_addr = {offset=&(symgot.value), type = COPY, sym=0}

Following a pointer

symgot = {value:&got_0x8, size: 8, ...}

get_exec_linkmap = {offset=&(symgot.value), type = COPY, sym=0}

get_l_next = {offset=&(symgot.value), type = 64, sym=0, addend=0x18}

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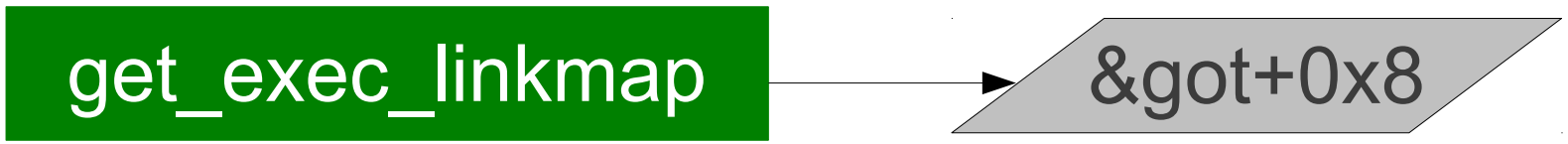

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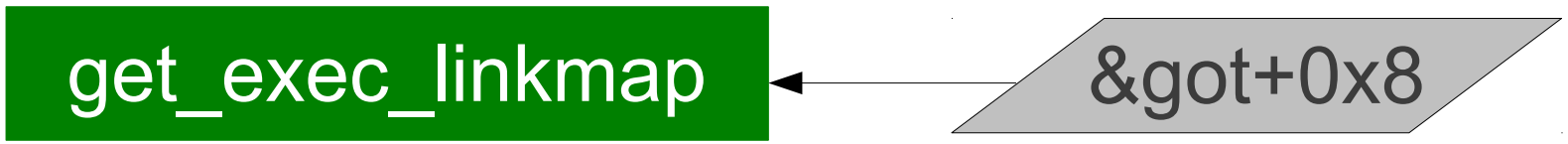

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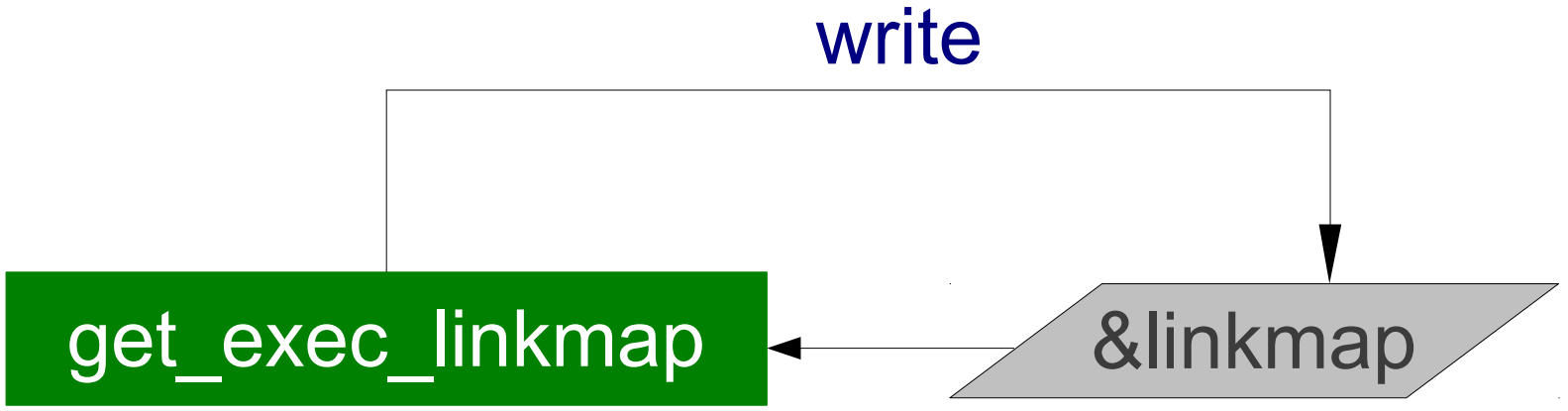

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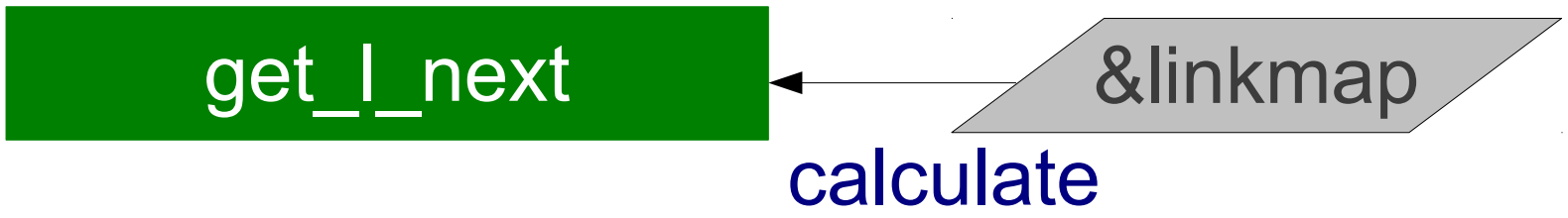

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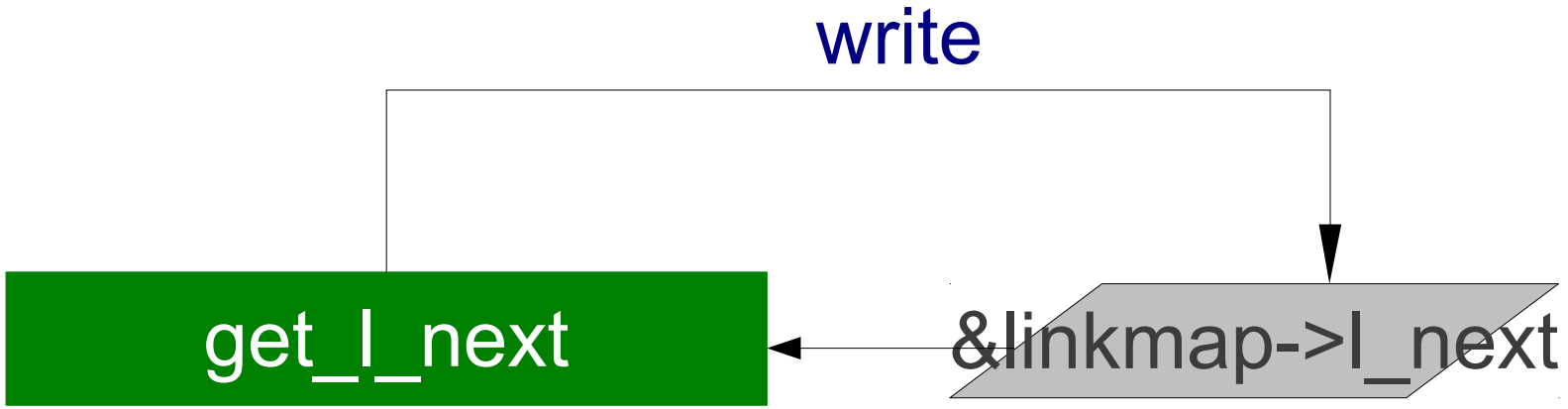

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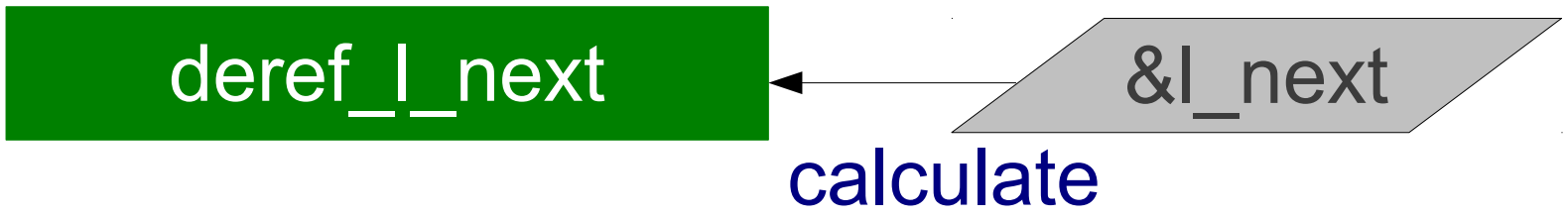

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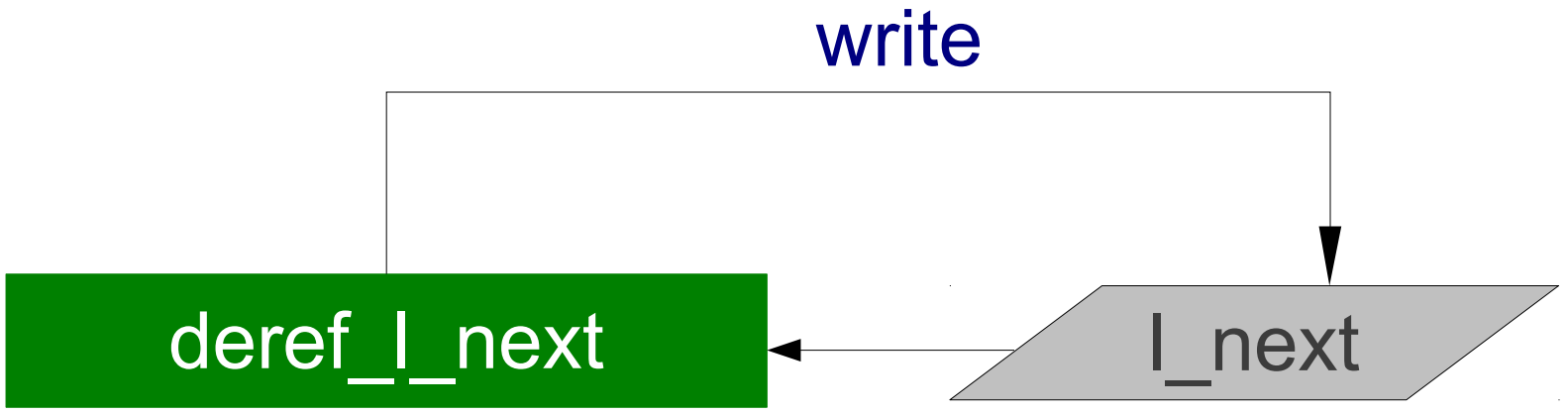

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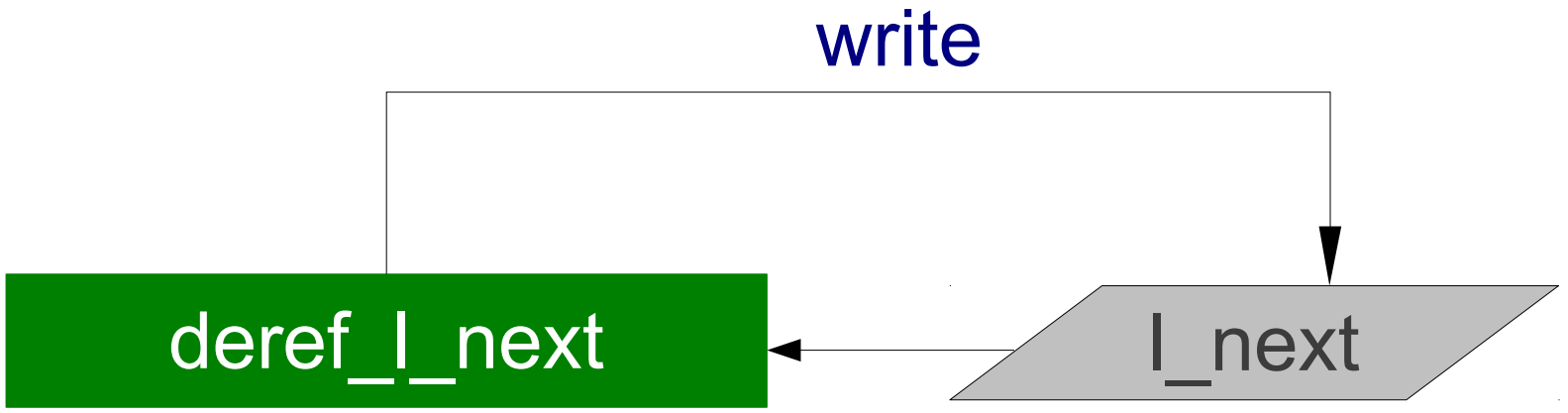

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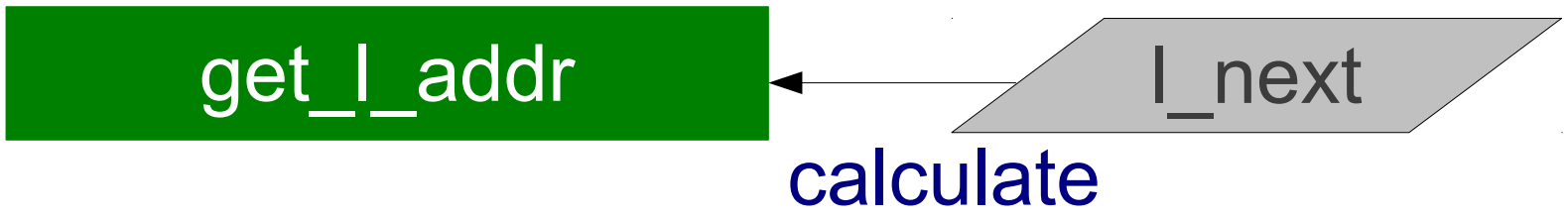

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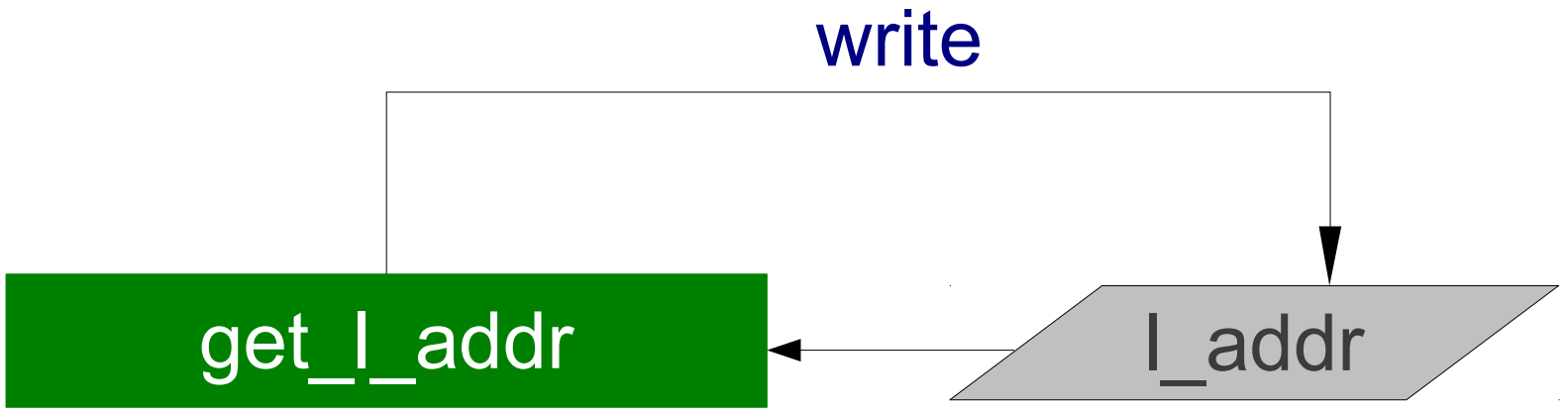

symgot's value is base address of some ELF object

Demo exploit

- Built backdoor into Ubuntu's inetutils v1.8 ping
- Ping runs suid as root
- Given ”-t <string>”
  - -t, --type=TYPE send TYPE packets
  - if (strcasecmp (<string>, "echo") == 0) ….
- Goals:
  - Redirect call to **strcasecmp** to **execl**
  - Prevent call to **setuid** that drops root privs
  - Work in presence of library ASLR

Demo exploit

- Goals:
  - Redirect call to strcasecmp to execl
    - Set strcasecmp's GOT entry to &execl
  - Prevent privlege drop
    - Set setuid's GOT entry to & retq instruction
- Found offset to exel and a retq instruction in glibc
- Need to find base address of glibc @ runtime
- Use link_map traversal trick!
  - The rest is simple addition/relocation

(video of demo was here)

Thanks!

- Sergey Bratus
- Sean Smith

Inspirations:

- The grugq
- ERESI and Elfsh folks
- mayhem
- Skape

Questions?