ELF Eccentricities

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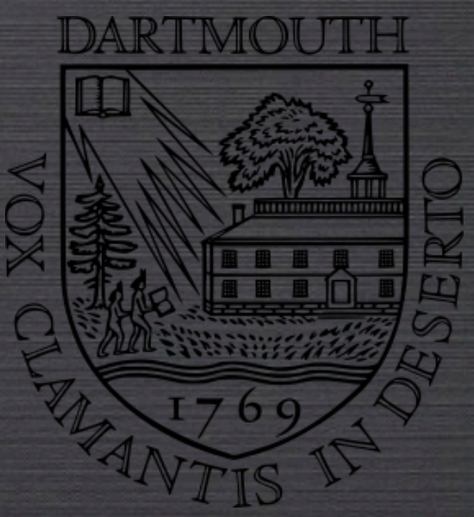


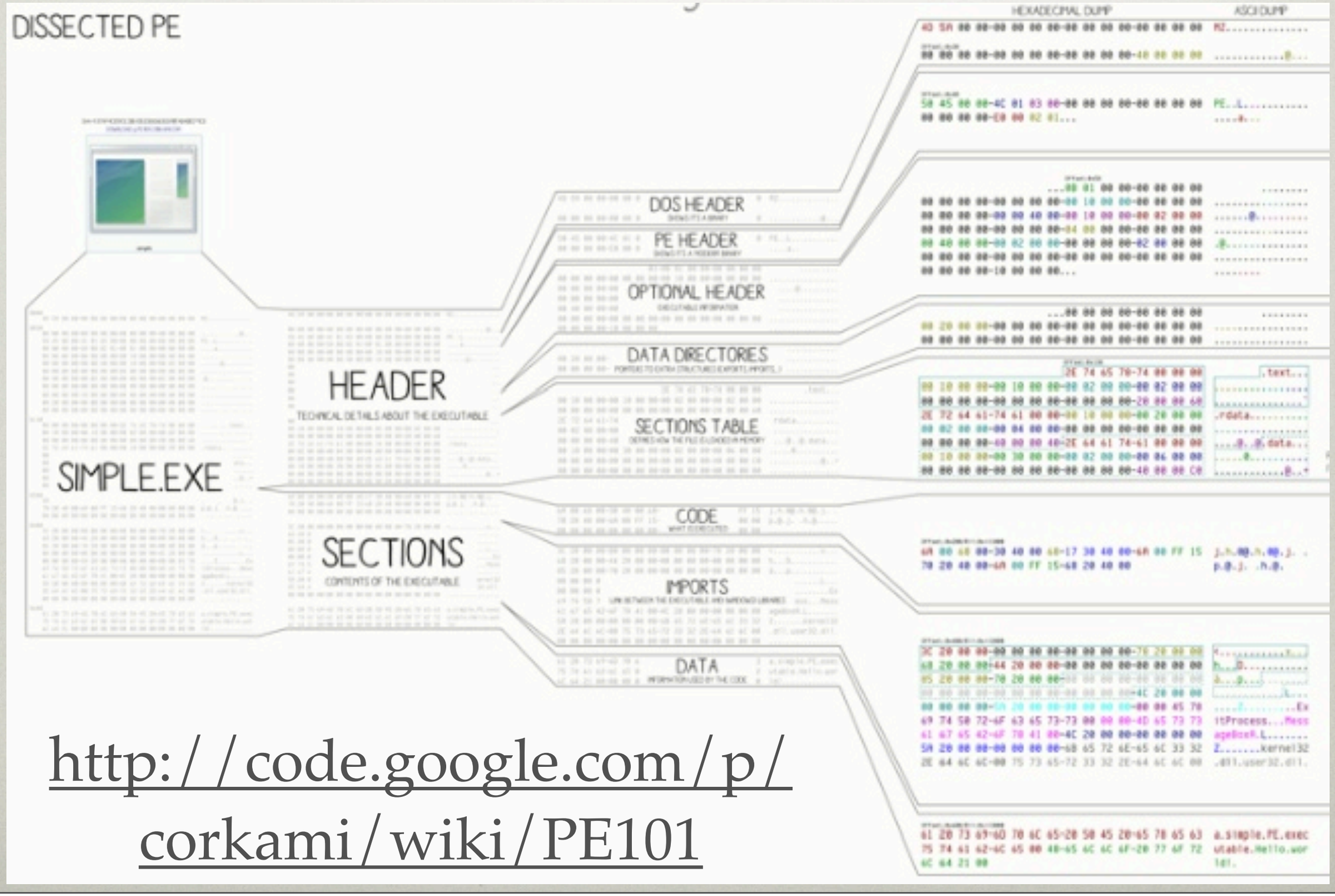
This talk brought to you by the letter "L"

- ELF: Executable **L**inkable Format
- Linking/loading is a complex **computation** on complex inputs
- Linking/loading paints **magical memory trees** (vma_structs, ...)
- Parsed by exec(), ld.so, IDA, ... - each **slightly differently**
- Full of mystery? "Invisible"?

ELFs in all the things

- Executables, **.so**, **.o**, coredumps, ...
- Replaced non-extensible AOUT
- Designed by System V working group, extremely extensible:
  - keeps code/data **intelligible** (sections, symbols, dynamic symbols)
  - allows code/data to **compose** (“link”)
  - allows code/data to **mutate** (relocs ~ASLR)

PE, a cousin of ELF



http://code.google.com/p/corkami/wiki/PE101

Mach-O, a cousin of ELF

"This space intentionally left blank"

More to come from @bxsays

Further Reflections on Trusting Trust (I)

- Ken Thompson, "Reflections on Trusting Trust", 1984
  - *"You can't trust code that you did not totally create yourself"*
- many links in the trust chain are '**invisible**' (down to "*well-installed microcode bugs*")

Further Reflections on Trusting Trust (II)

- What if there were **no bugs** in any given piece of sw/hw link of the trust chain?
  - What could go wrong then?
- What are the **execution models**/ computational strength of the links?
  - What can one do with **well-formed** crafted inputs?

The ELF/ABI case study

Compiler

Linker

ld.so (RTLD)

Relocator
("dl-machine")

Loader

binfmt_elf

#PF

A Whirlwind of Weird Machines

- Relocation entries + dynamic symbols = Turing machine on process' address space
- DWARF exception handling data + .eh_frame + Glibc = Turing machine
- GDT + IDT + TSS + page tables + #PF + #DF = Turing machine in ia32
- More coming :)

Langsec angle (1)

- "**Any Input Is A Program**"
  - Input **executes** on input handlers (drives state changes & transitions)
    - Only a **well-defined** execution model can be trusted
- Input handler is either a **recognizer** for the inputs as a well-defined language, or it's pwned (see **http://langsec.org/**)

Langsec angle (2)

- **Parse differentials create subtle vulns**
- **One input, two parsers**: A Tale of Woe
  - *"PKI Layer Cake"* X.509 parser differentials, Dan Kaminsky, Meredith L. Patterson, Len Sassaman
  - Cert parser differentials between CAs and clients broke the X.509 trust model as we know it

Langsec angle (3)

- Two views of the same data => confusion
  - Redundant data: which version is taken?
  - How many ELF parsers in ABI toolchain? Kernel's binfmt_elf loader vs user ld.so

Der Tragödie erster teil

tour de Elf

(with a dash of fail)

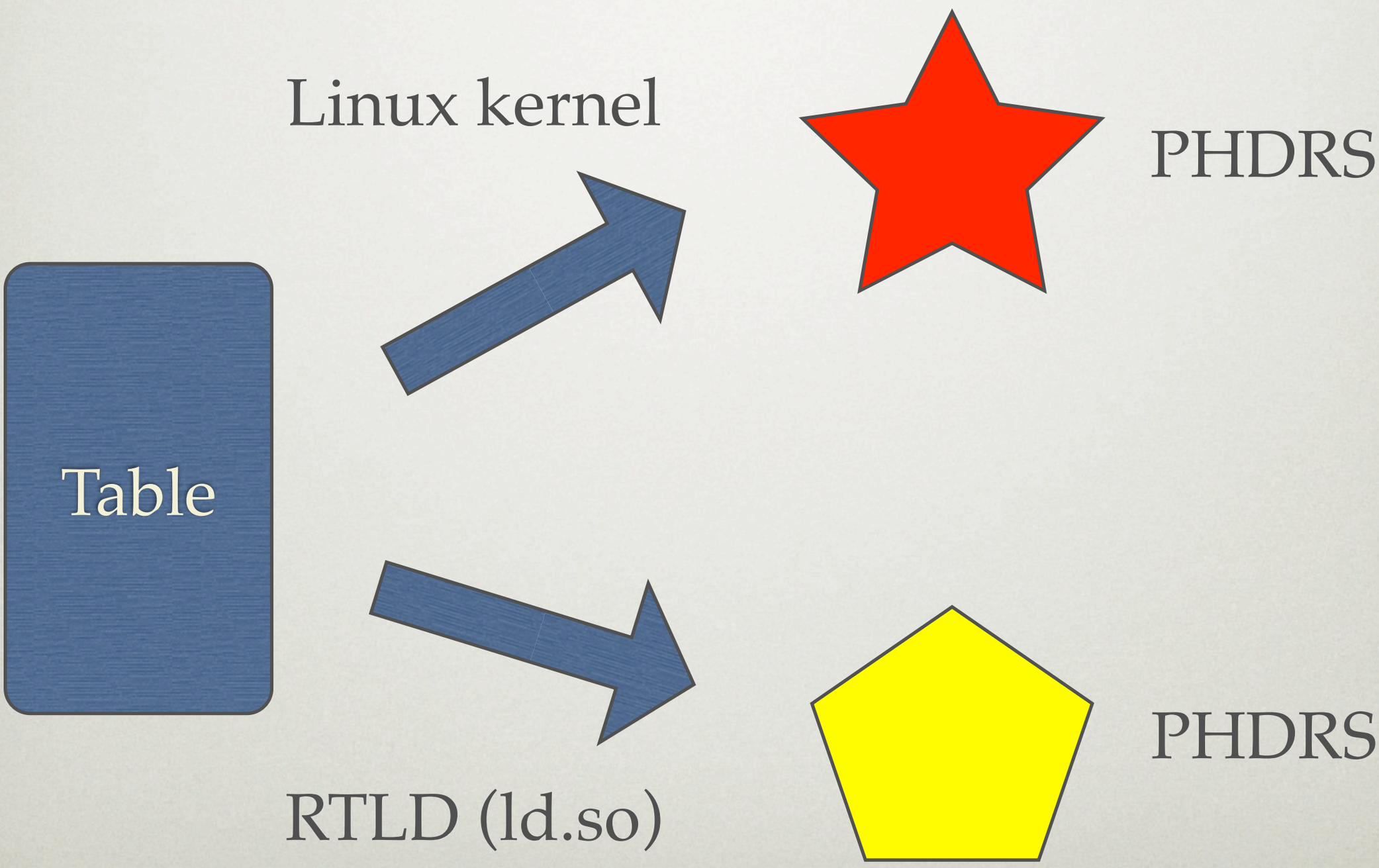
A Beautiful Dream...

- Tools don't need different parsers for libraries, object files and executables
- Tools work for all platforms
- Postel's principle: Allow tools to ignore information they don't understand, change tools only as needed
- Otherwise, no .so or ASLR

...AND NOW WE WAKE UP

- One libelf to parse them all?
  - Everyone **still** builds their own impl.
- "Coming to the B-horror cinema near you!"
  - **Revenge of the Design Committee**
  - **Assault of the Performance Hack**
  - **The Night of the Unchecked Assumption**

Double the parsing, double the fun



ELF header

- Generic information (Version, architecture, file type, etc.)
- Refers to **section table & program header table**

```
typedef struct {
        unsigned char   e_ident[16];
        Elf32_Half      e_type;
        Elf32_Half      e_machine;
        Elf32_Word      e_version;
        Elf32_Addr      e_entry;
        Elf32_Off       e_phoff;
        Elf32_Off       e_shoff;
        Elf32_Word      e_flags;
        Elf32_Half      e_ehsize;
        Elf32_Half      e_phentsize;
        Elf32_Half      e_phnum;
        Elf32_Half      e_shentsize;
        Elf32_Half      e_shnum;
        Elf32_Half      e_shstrndx;
} Elf32_Ehdr;
```

Section Headers

- Label a range of offsets
- Represent 2 views of the file
  - Offset view
  - Address view
- **Labels** for **byte subsets** of the file

```
typedef struct
{
  Elf32_Word sh_name;
  Elf32_Word sh_type;
  Elf32_Word sh_flags;
  Elf32_Addr sh_addr;
  Elf32_Off  sh_offset;
  Elf32_Word sh_size;
  Elf32_Word sh_link;
  Elf32_Word sh_info;
  Elf32_Word sh_addralign;
  Elf32_Word sh_entsize;
} Elf32_Shdr;
```

Section header fun

- Do not guarantee non-overlay
  - "What is at offset/address x mean?"
  - **Context sensitive**
  - We could just reject overlap
  - Yet another obfuscation talk?
- Loader has to parse large section table
  - OMG 30 entries!

Program headers (Segments)

- Loader ignores sections
- Has separate ‘program header table’.
- A **different label system**
- != x86 hardware segments

```
typedef struct
{
  Elf32_Word p_type;
  Elf32_Off  p_offset;
  Elf32_Addr p_vaddr;
  Elf32_Addr p_paddr;
  Elf32_Word p_filesz;
  Elf32_Word p_memsz;
  Elf32_Word p_flags;
  Elf32_Word p_align;
} Elf32_Phdr;
```

IDA uses sections, kernel uses segments

```
; =============== S U B R O U T I N E =======================================

; Attributes: bp-based frame

                public main
main            proc near               ; DATA XREF: _start+1D↑
                push    rbp
                mov     rbp, rsp
                mov     edi, offset hello_2 ; "Hello, World\n"
                call    _puts
                pop     rbp
                retn
main            endp

; ---------------------------------------------------------------------------
```

```
$./hello
dlroW ,olleH
```

Memory vs. File

- Most parsers **read**() file
- Some work on the memory **mmap**()-ed version
- Assume almost **linear** map
- The file describes its own memory layout

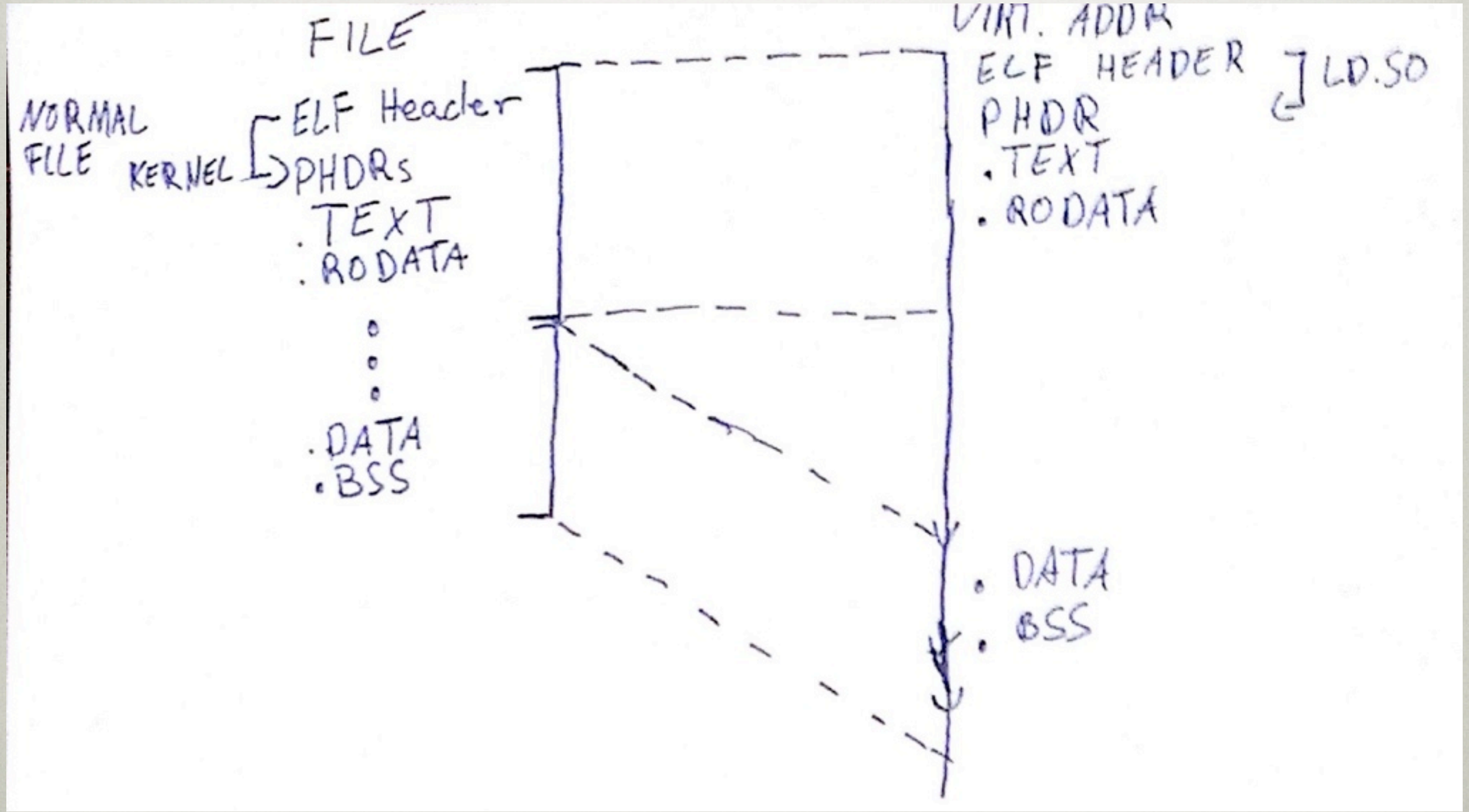
Program headers (I)

- PT_LOAD:
- “Map these bytes (+ some /dev/null) to this address range”
- Overlap: each PT_LOAD is a **mmap()**
- **Evad3rs** noted that mmap **replaces** existing mappings
- **Order** of PT_LOAD is important, but that’s not in the spec.

The birth of an Elf

1. Kernel reads PHDR table into buffer
2. One mmap per PT_LOAD
3. Loads PT_INTERP
4. Sends (addr of first PT_LOAD)+ hdr.phoff to loader ("**AUX vector**")
5. Loader looks for & parses **PHDRs** starting at the address in aux vector

LD.SO PHDR


FILE
NORMAL FILE
KERNEL
ELF Header
PHDRs
.TEXT
.RODATA
.DATA
.BSS
VIRT. ADDR
ELF HEADER
PHDR
.TEXT
.RODATA
LD.SO
.DATA
.BSS

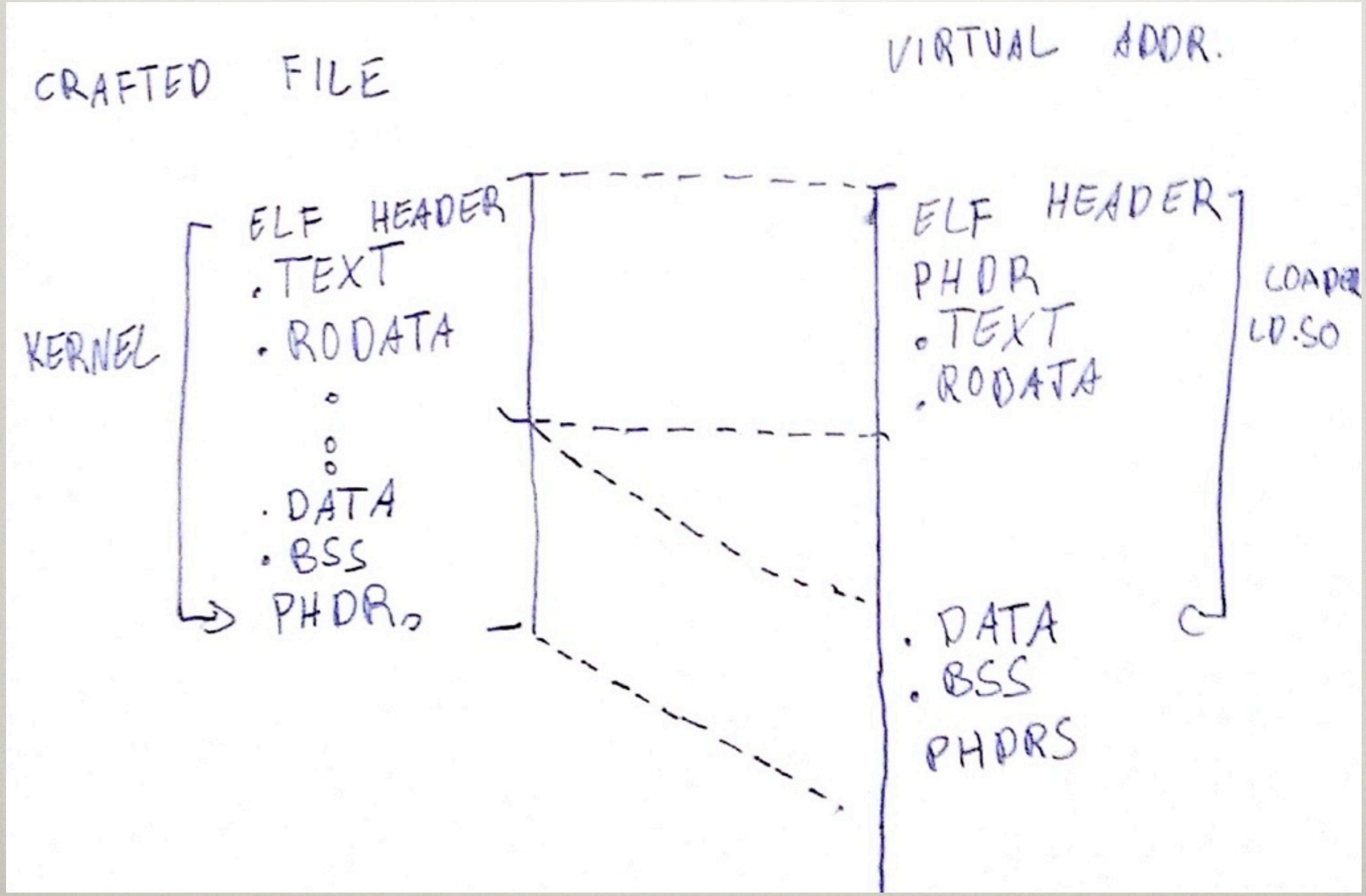
Obligatory kernel source

```
/*Redacted from binfmt_elf.c, Linux 3.4, GPLv2*/
elf_phdata = kmalloc(size, GFP_KERNEL);
kernel_read(bprm->file, loc->elf_ex.e_phoff, (char
*)elf_phdata, size)
for(phdrs...){
/*..., scans for PT_INTERP and PT_LOAD*/
if(phdr->p_type == PT_LOAD)
if (!load_addr_set) {
    load_addr = (elf_ppnt->p_vaddr - elf_ppnt-
>p_offset);
    load_addr_set = 1;
 }
}
NEW_AUX_ENT(AT_PHDR, load_addr + exec->e_phoff);
                    /*^^^^^^^^^^^^^^^^^^^^^^^^^^ FAIL!*/
```

PHDR bug

- Works Just Fine™ if program headers mapped as first segment.
- Otherwise, points somewhere else
- We can “finger-paint” memory to our liking, and ld.so will use **different** PHDRS
- Hide your PHDRs, the reverse engineers are coming!

Crafted file



What do we get?

- Can't map memory, the kernel does that
- PT_DYNAMIC

Dynamic section

- The loader gets symbol tables, relocations, etc., from the **.dynamic** section
  - which it finds through the PT_DYNAMIC PHDR
- Only cares about **address**, not file offsets or sections

How Tools find dynamic

- Program Header, by virtual address or offset
- Section
- Symbol

Dynamic entries

- DT_STRTAB-> Strings (e.g. symbols)
- DT_SYMTAB -> Symbols
- DT_RELA -> Relocations (ASLR, shlib)
- DT_NEEDED -> imported shared libraries

SHARED LIBRARIES

- Shared libraries (and PI executables) are loaded at a random address
- Allocate space for entire library, then remap
  - Size: End_of_last_PHDR - start_of_first_PHDR
  - **Deranged** PT_LOADs (ranges “normally” assumed sorted by loader), integer overflow?
  - Can change memory permissions elsewhere in program

"Memory finger-painting"

- PHDRS control vma structs in kernel
- Different paths: mmap(), mmap()->mprotect(), in-kernel parser
- Page-granularity of vmas not reflected in format
- Rounding in various places, overlap
- Combining different paintings

Rewriting programs in memory with ld.so?

- We control **ld.so**'s idea of all relevant sections: GOT, dyn symbols, ...
- **ld.so** resolves (what it thinks are) symbols, writes (what it thinks is) GOT
- Fun way to rewrite your program via crafted .dynamic + library symbols

Symbols

- Symbol is a name for addresses(.so and +x) or offsets(everything else). That is a convention, tools might break if you mix
  - **.dynsym** (loader) vs **.symtab** (linker,debugger)
  - Undefined symbols, imported from somewhere else
  - Weak symbols for ‘default values’
  - Can hide symbols from linker with versioning

Relocations

- Fill in missing references to other objects
- *Theory:* 'Replace this bit of program/data with some computation on this symbol'
- *Reality:* Read memory(.rela, .dynsym), compute, write memory -- **anywhere**
- @bxsays: **Turing machine!** (see elf-bf-tools on Github, our talk noon tomorrow)

What is linking?

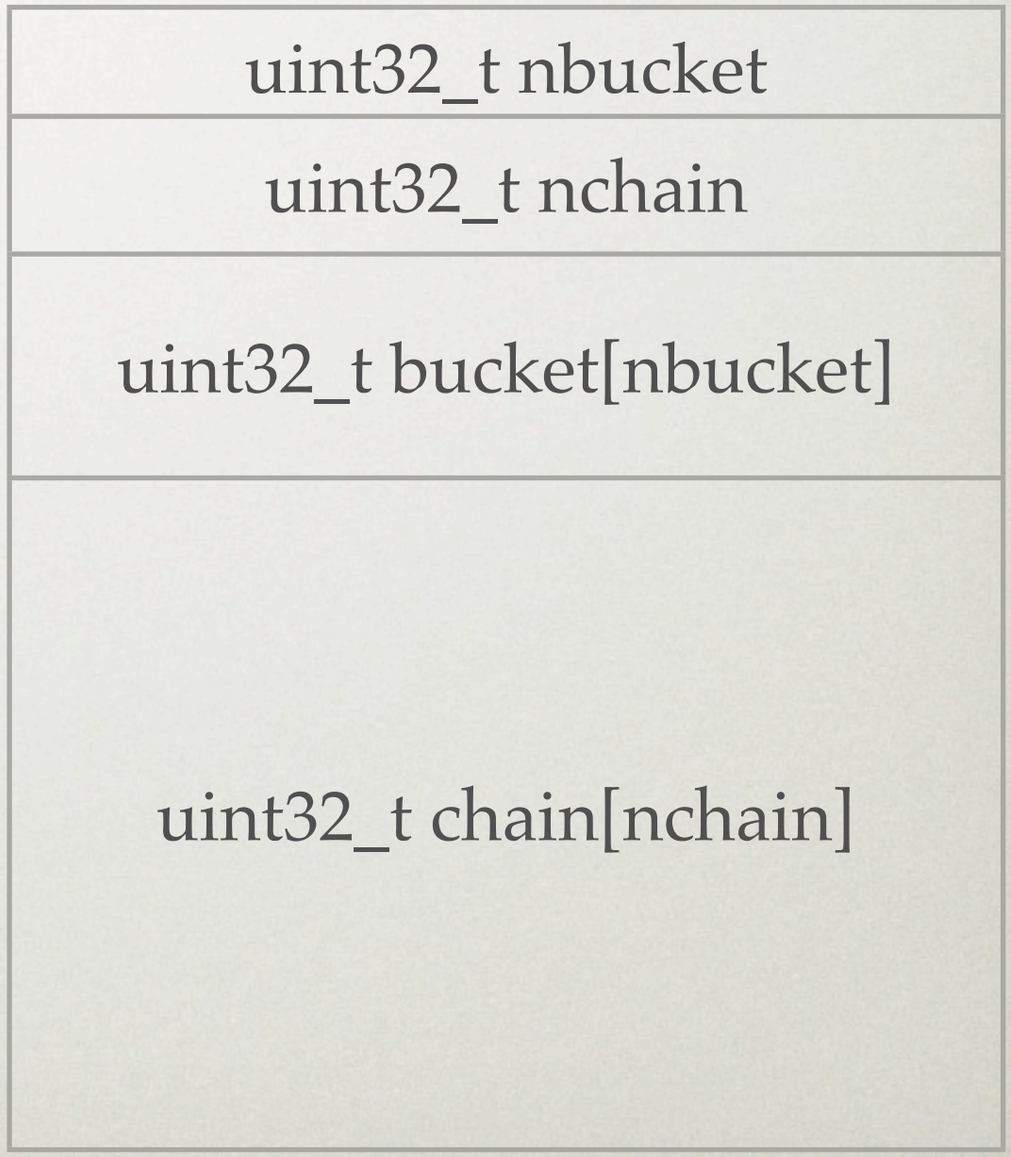
- We are working on formalizing this
- Roughly:
  - Combine sections from different ELF objects
  - Resolve symbols
  - Apply relocations
- Code at the end of the talk

But it has to be fast

- Symbol lookups by walking string table are inefficient
- DT_HASH and DT_GNU_HASH
  - hashtable Symbol name -> string

DT_HASH

- Hashtable, simple hash
- Each hash bucket can point to one symbol
- chain has ‘next’ link for each symbol



Walking the hash table

```
/*dl-lookup.c:268*/
for (symidx = map->l_buckets[*old_hash %
map->l_nbuckets];
     symidx != STN_UNDEF;
     symidx = map->l_chain[symidx])
{
     sym = check_match (&symtab[symidx]);
     if (sym != NULL)
       goto found_it;
}
```

What happens if these checks never succeed?

DT_HASH_LOOPING:
"The Red Queen Break-Point"

- Collision entry points to itself
- Resolver hangs
- Without hash(or DT_GNU_HASH) it will work fine
- Can make only some symbols hang
- Breakpoints

uint32_t nbucket
uint32_t nchain
uint32_t bucket[nbucket]
uint32_t chain[nchain]

Der Tragödie Zweiter teil

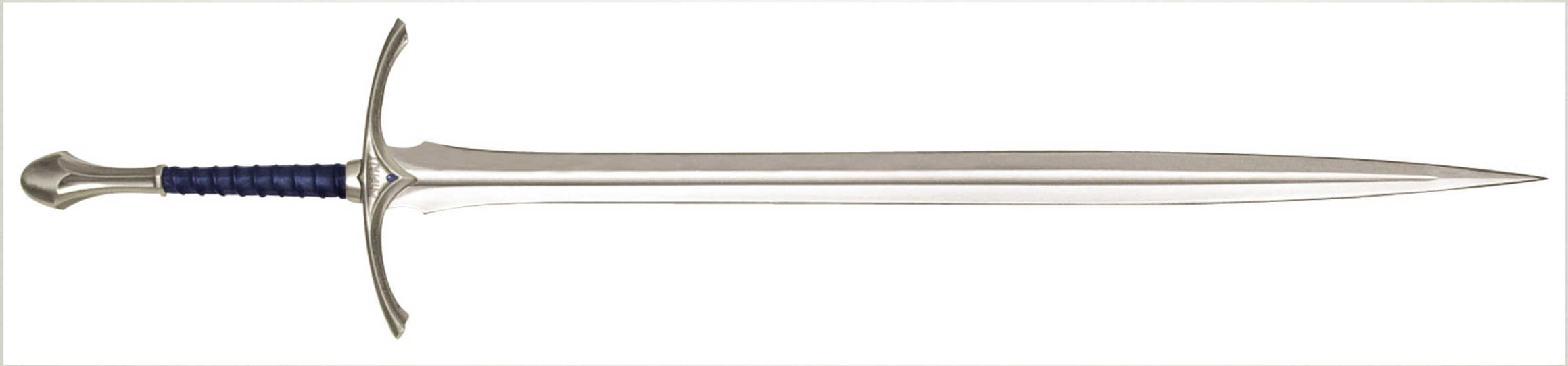
In Soviet Russia,

Mithril forges ELF

Inspiration: ElfSH

- ERESI reversing framework by Julien Vanegue and team
- **.bx** and I are big fans!
- ELF handled with libelfsh
- just went back to active development; ELF parsing developed as needed => some bugs

What to do differently



- ERESI modifies the binary as little as possible
- In-memory representation close to on-disk
  - Rewrites much of the binary on change
- Sometimes (inevitably), misses a dependency and breaks the binary

MITHRIL

- Elves smithe powerful swords and chain armour from mithril
- We cut and link ELFes with Mithril
- Parse ELF into a ‘context-free’ representation, write representation into ELF
- Files differ, but semantically identical

MITHRIL

- Ruby prototype
- Rewrites Ubuntu 12.04 64-bit - except
- github.com/jbangert/mithril

Binarysmithing 101

- Injecting code, ordinary swords:
  - Shift section headers, inject section
  - Shift sections in file, inject data
  - Update PHDRS
- Injecting with Mithril:

```
mysect = Elf::Progbits.new(".inject")
mysect.data.write "Foo\0"
mysect.flags =  SHF::SHF_ALLOC
file.progbits.push mysect
```

Graduate binarysmithing

- Inject symbol:

```
file.symbols << Symbol.new(...)
```

- Inject relocation:

```
file.relocations << Relocation.new()
```

- Mithril::Writer.to_file(“foo”,file)
- Mithril takes care of the rest

Let's roll our own linker

- Showcase the conciseness of Mithril
- What does it really mean to 'link' a binary? Upper bound by construction

Useless metrics !

- sloccount binutils-2.20:
  - ld:115138, bfd:317996
    - gold:56673 is a better comparison..
- wc -l bin/mithril-ld : 76
- sloccount mithril-0.0.1: 2771

Invoking it

```
file = Elf::linkfiles(Elf::newfile,
ARGV[1..-1].map{|x| Elf::Parser::from_file(x)})

Elf::Writer.to_file(ARGV[0], file)
```

Let's have a source walkthrough

```
require 'mithril'
module Elf
def self.newfile
  ElfFile.new.tap {|x|
    x.filetype = ElfFlags::Type::ET_EXEC
    x.machine = ElfFlags::Machine::EM_X86_64
    x.version = ElfFlags::Version::EV_CURRENT
    x.flags = 0
    x.bits = 64
    x.endian  = :little
    x.interp =  "/lib64/ld-linux-x86-64.so.2"
  }
end
```

State

```
def self.linkfiles(outfile, infiles)
    progbits = {}
    symbols = {}
    sect_map = {}
    sect_offsets = {}
    symbols = {}
```

```
infiles.each {|infile|
      #link actual data
      (infile.progbits + infile.nobits).each
{|inbit|
        outbit = (progbits[inbit.name] ||=
Elf::ProgBits.new(inbit.name))
        outbit.flags |= inbit.flags
        outbit.align = [inbit.align,
outbit.align].max
        outbit.sect_type = inbit.sect_type
        sect_offsets[inbit] =
outbit.data.tell
        sect_map[inbit] = outbit
        outbit.data.write inbit.data.read
#TODO: Handle align
      }
```

```
    infile.symbols.each {|symbol|
          next if symbol.name.empty?
          next unless [Elf::STT::STT_OBJECT, Elf::STT::STT_FUNC,
Elf::STT::STT_COMMON, Elf::STT::STT_NOTYPE].include? symbol.type

          if (symbols.include? symbol.name)
            next if symbol.weak? or symbol.undefined?
            raise ArgumentError.new "Duplicate definition of symbol
#{symbol.name}"  unless symbols[symbol.name].weak?  or
symbols[symbol.name].undefined?
          end
          symbols[symbol.name] = symbol.clone.tap{|outsym|
            unless outsym.undefined?
              outsym.sectoffset += sect_offsets[outsym.section]
              outsym.section = sect_map[outsym.section]
            end
          }
        }
```

```
 progbits.values.each {|progbit| outfile.progbits
<< progbit   }
    symbols.values.each {|sym| outfile.symbols <<
sym}

    infiles.map(&:relocations).flatten.each {|rela|
      outfile.relocations << rela.clone.tap{|x|
        x.offset += sect_offsets[x.section]
        x.section = sect_map[x.section]
        name = x.symbol.name
        x.symbol = symbols[name]
        x.is_dynamic = true
        raise ArgumentError.new "Undefined symbol
#{name}" if(x.symbol.nil?)
      }
    }
```

```
raise "Undefined entry point
_start " unless symbols.include?
"_start"
    entry = symbols["_start"]
    entry.section.addr = 0x40000
    outfile.entry =
entry.sectoffset +
entry.section.addr

    return outfile
```

Missing features

- Section Symbols are handled poorly
  - (That currently breaks crt1.o, which has the _start for libc)
- No STF_MERGE, STT_COMMON, other ‘unusual’ extensions
  - Sorry, we don’t link Fortran here

What to do with it

- Normal ld works, so keep using it
- But load up mithril in Pry / IRB and play around with binaries
- Metadata tricks don't have to be arcane!

Shoutouts!

- LANGSEC conspiracy (**http://langsec.org/**)
- Corkami http://code.google.com/p/corkami/
- ERESI project team, past and present
- TinyELF http://www.muppetlabs.com/~breadbox/software/tiny/teensy.html
- The Grugq & Silvio Cesare
  (for hooking Sergey on ELF)
- Phrack \cite{Phrack XX:XX}

Questions?

- @julianbangert, @sergeybratus
- github.com/jbangert/mithril
- gem ‘elf-mithril’
- Needs gem ‘bindata’, github: ‘jbangert/bindata’ (Fork not merged back yet)
- See also USENIX WOOT 2011, 2013 for our “weird machines” papers