Finding library subroutines in stripped statically-linked binaries

findmagic

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obligatory tl;dr me slide

- Computer Science student
- Member of the H4x0rPsch0rr CTF-Team and CTF-Player for fun (and sometimes profit)
- Interested in reverse engineering for long time
- Hates QR-Codes

Preliminary audience questions

Who of you has...

- basic knowledge of graph theory?

Preliminary audience questions

Who of you has...

- basic knowledge of graph theory?
- reverse engineered a statically linked binary at least once?

Problem description

Why?

- Traditional pattern-matching: exact library needed for decent results
- Works reasonably well in homogenous environments like MSVCRT
- Open source libraries?
- Embedded devices?

Problem description

Why?

So, what are we doing if we cannot have symbols?

- Looking at the arguments?
- Looking at suspicious constants?
  Think of `0x8080808080` for `strlen(3)`

Let's automate this!

However, there are caveats:

- Finding arguments is not a trivial task.
- What makes a constant suspicious?

Problem description

Why?

However, there are caveats:

- Finding arguments is not a trivial task.
- What makes a constant suspicious?

But automating gives new perspectives:
Comparing callgraphs!

- Program is a set of attributed graphs $G = (N, B)$
- Nodes N are functions
- Branches B are calls between functions

We need:

- A string definition

$$
\begin{aligned}
&(\forall (i,c) \in str : c \geq \texttt{0x20} \wedge c \leq \texttt{0xDF} \\
&\quad \vee c = \texttt{0x0A} \vee c = \texttt{0x0D} \vee c = \texttt{0x09} \vee c = \texttt{0x00}) \\
&\quad \wedge |str| > 1 \\
&\quad \wedge (\forall (i,c) \in str \,|\, i = \max(i, str) : c = \texttt{0x00}) \\
&\quad \wedge (\forall (i,c) \in str \,|\, i \neq \max(i, str) : c \neq \texttt{0x00})
\end{aligned} \tag{1}
$$

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Printable characters from extended ASCII ...

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$$

... and `\n`, `\r`, `\t` and `0x00` ...

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\end{aligned} \tag{1}
$$

... with a minimum length of 2 ...

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\end{aligned} \tag{1}
$$

... where the last character is `0x00` and no other character is `0x00`.

We need:

- A node definition
  $N = (n, s, C, S, I)$
  - n: Function name
  - s: Function address
  - C: Multiset of constant values
  - S: Multiset of cross-referenced strings
  - I: Ordered multiset of the machine instructions

Objective: Generate a bijective mapping $M = N_1 \to N_2$

- N_1: known library function
- N_2: function inside the target library

1. Acquire target library with debug symbols

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2. Build the graphs for it

Algorithm Design

Get crackin'

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3. Build graphs for the binary we analyse

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2. Build the graphs for it
3. Build graphs for the binary we analyse
4. Match them

Do we need exactly the same binary used for linking?

- Short answer: no.

Do we need exactly the same binary used for linking?

- Short answer: no.
- Long answer: it depends.

- A reasonably close version is enough
- Watch out for compiler flags
- Also problematic: assert()

Caution: real world example

```
assert((unsigned long) (old_size) < (unsigned long) (nb + MINSIZE));
```

with relocation:

```
(unsigned long) (old_size) < (unsigned
     long) (
  nb + (unsigned long)(
    (((__builtin_offsetof (struct
         malloc_chunk, fd_nextsize)) +
        (
          (2 * (sizeof(size_t))) - 1
      ))
      & ~(
        (2 * (sizeof(size_t))) - 1
))))
```

No code, but debug strings vary!

without relocation:

```
(unsigned long) (old_size) < (unsigned
     long) (
  nb + (unsigned long)(
    (((__builtin_offsetof(struct
         malloc_chunk, fd_nextsize)) +
        ((2 * (sizeof(size_t)) <
             __alignof__ (long double) ?
           __alignof__ (long double) :
           2 * (sizeof(size_t))
         ) - 1))
      & ~(
        (2 * (sizeof(size_t)) <
             __alignof__ (long double) ?
          __alignof__ (long double) :
          2 * (sizeof(size_t))
        ) - 1
))))
```

1. Iterate over subroutines
2. Iterate over the instructions of these subroutines
3. If something interesting is found, add it to the corresponding list[1]

[1] See the paper for a marvellous formal definitions for this

- `call` instructions add a new branch to the functions callgraph
- Additionally for Intel x86_64 architecture:
- Only if it's a near call - opcode `0xE8`
- This ensures we're in the same section
- Other architectures may need different conditions!

- Look for something that loads a pointer (x86_64: `lea`, `mov`)
- Check if it's a string by our definition
- If so, add it to the Strings of the current function

- We don't want to add pointer arithmetic as constants
- Interesting constants are often bitmasks
- Thus, we limit ourselves to the immediates of `and`, `or`, `xor` and `mov`
- Optionally, we may exclude further by doing value checking on the constant

Isomorphism:

- Ancient greek: *isos* = equal and *morphe* = shape
- Mathematical way to compare the structure of objects

Choosing the right algorithm:

- Ullmann's algorithm
- Nauty (**n**o **aut**omporphism, **y**es?)
- VF2

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Choosing the right algorithm:

- Callgraphs cannot be considered randomly connected
- Some functions imply calls to other functions
- `malloc()` & `free()`, `accept()` & `close()`, ...
- VF2 is very fast in this situation
- Also, VF2 can check semantic equality of the nodes in the same step

VF2

- $G_1 = (N_1, B_1)$, $G_2 = (N_2, B_2)$
- Mapping $M \subset N_1 \times N_2$
- M must be a bijective function
- M must not alter the branch structure

- State Space Representation (SSR) s
- Essentially a set of tuples (n_1, n_2)
- $M(s)$ denotes a partial mapping
- Two subgraphs $G_1(s)$ and $G_2(s)$ can be derived, containing only the nodes in the matching and the branches connecting them
- Same for $M_1(s)$, $M_2(s)$, $B_1(s)$, $B_2(s)$

VF2

- Transition from state s to s': $s' = s \cup \{(n, m)\}$
- But: only a small set of these states are *consistent*
- We introduce *k-lookahead rules* to conclude wether a consistent state can be reached after k steps
- These rules will be called *feasibility rules*

Feasibility function: $F(s, n, m) = F_{syn}(s, n, m) \wedge F_{sem}(s, n, m)$

- $F_{syn} \rightarrow$ **syntactic** feasibility
- $F_{sem} \rightarrow$ **semantic** feasibility

- Initial state is empty, i.e. $M(s_0) = \varnothing$
- In each step, compute $P(S)$, the node pairs of candidates to be added
- $T_n^{in} \rightarrow$ nodes with branches ending into $G_n(s)$
- $T_n^{out} \rightarrow$ nodes with branches starting from $G_n(s)$
- $P(s) = \{(n, m) | n \in T_1^{out}, m \in T_2^{out}\}$ if no T_n^{out} is empty, T_n^{in} otherwise
- If $P(s)$ is still empty, backtrack until a state s is reached with $P(s)$ containing not examined node pairs

Check predecessors of current node:

$$R_{pred}(s,n,m) \iff$$
$$(\forall n' \in M_1(s) \cap \mathrm{Pred}(G_1,n)\, \exists\, m' \in \mathrm{Pred}(G_2,m) \mid (n',m') \in M(s)) \wedge$$
$$(\forall m' \in M_2(s) \cap \mathrm{Pred}(G_2,m)\, \exists\, n' \in \mathrm{Pred}(G_1,n) \mid (n',m') \in M(s))$$

Check successors of current node:

$$
\begin{aligned}
&R_{succ}(s,n,m) \iff \\
&(\forall n' \in M_1(s) \cap \mathrm{Succ}(G_1,n)\ \exists\, m' \in \mathrm{Succ}(G_2,m) \mid (n',m') \in M(s)) \wedge \\
&(\forall m' \in M_2(s) \cap \mathrm{Succ}(G_2,m)\ \exists\, n' \in \mathrm{Succ}(G_1,n) \mid (n',m') \in M(s))
\end{aligned}
$$

1-lookahead:

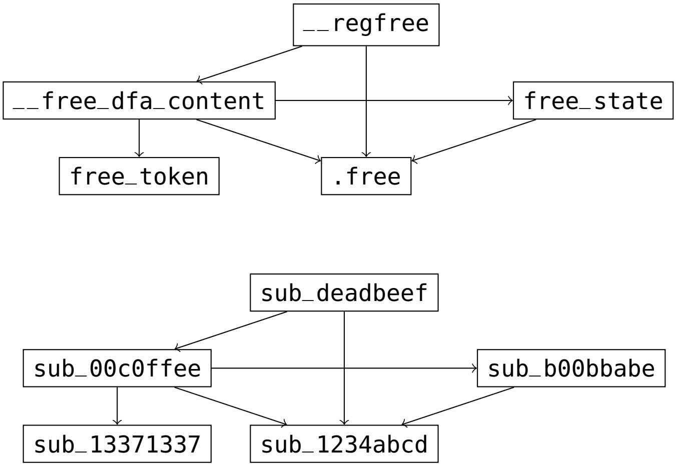
$$R_{in}(s,n,m) \iff$$
$$(\left|\mathrm{Succ}(G1,n) \cap T_1^{in}(s)\right| = \left|\mathrm{Succ}(G2,m) \cap T_2^{in}(s)\right|) \wedge$$
$$(\left|\mathrm{Pred}(G1,n) \cap T_1^{in}(s)\right| = \left|\mathrm{Pred}(G2,m) \cap T_2^{in}(s)\right|)$$

$$R_{out}(s,n,m) \iff$$
$$(\left|\mathrm{Succ}(G1,n) \cap T_1^{out}(s)\right| = \left|\mathrm{Succ}(G2,m) \cap T_2^{out}(s)\right|) \wedge$$
$$(\left|\mathrm{Pred}(G1,n) \cap T_1^{out}(s)\right| = \left|\mathrm{Pred}(G2,m) \cap T_2^{out}(s)\right|)$$

2-lookahead:

$$R_{new}(s,n,m) \iff$$
$$(\left|\widetilde{N}_1(s) \cap \mathrm{Pred}(G_1,n)\right| = \left|\widetilde{N}_2(s) \cap \mathrm{Pred}(G_2,m)\right|) \wedge$$
$$(\left|\widetilde{N}_1(s) \cap \mathrm{Succ}(G_1,n)\right| = \left|\widetilde{N}_2(s) \cap \mathrm{Succ}(G_2,m)\right|)$$

Example:



__regfree
__free_dfa_content
free_state
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.free
sub_deadbeef
sub_00c0ffee
sub_b00bbabe
sub_13371337
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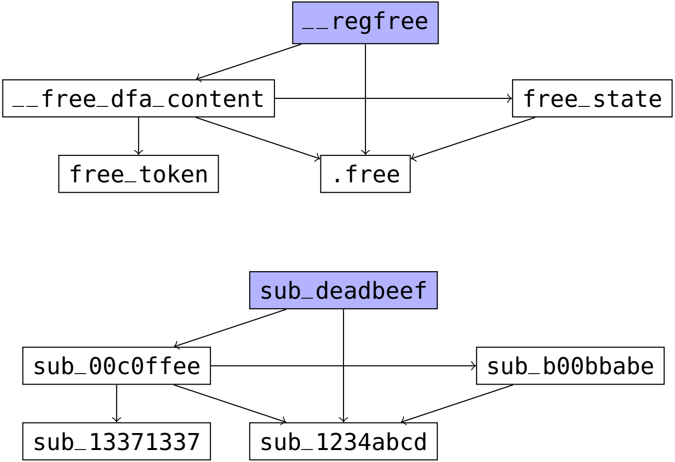

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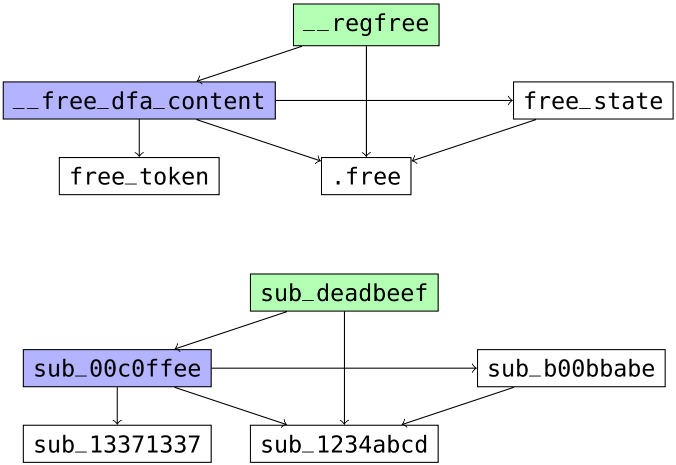
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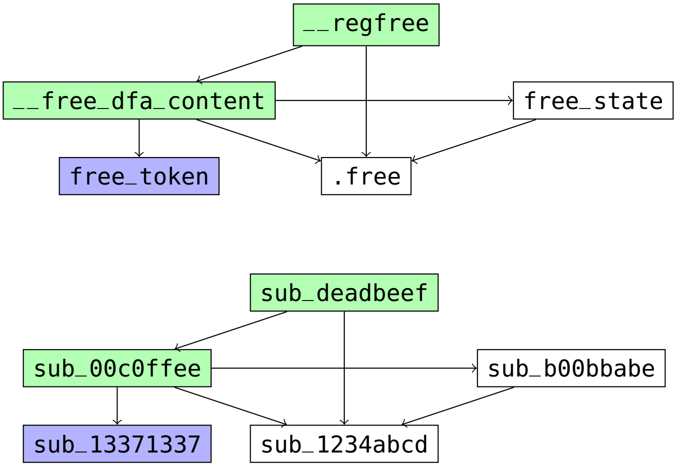

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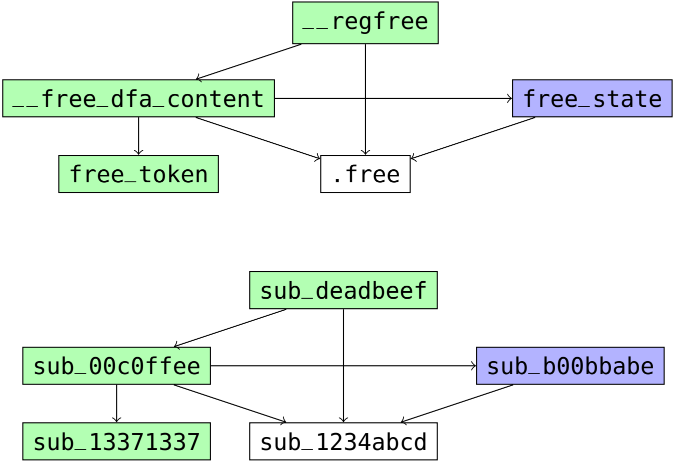
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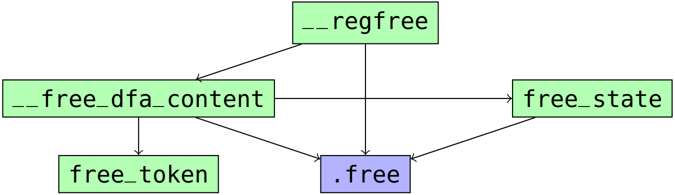
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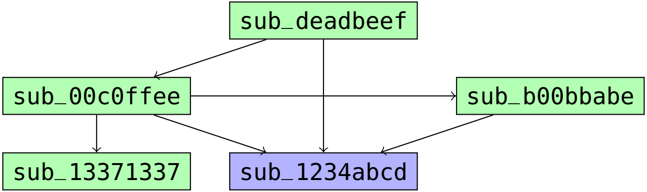
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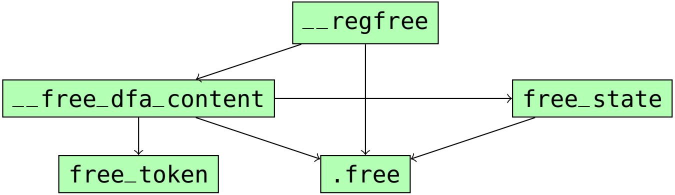

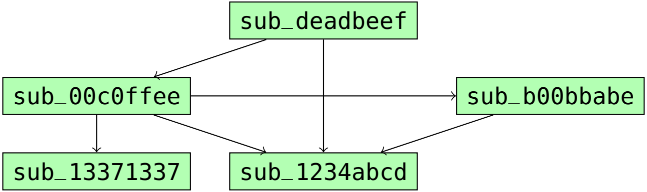

Semantic feasibility: We define a compatibility relation $\approx$

$$
\begin{aligned}
n \approx m \iff \\
(\forall c \in C_n \, \exists \, c' \in C_m | c = c') \wedge \\
(\forall c \in C_m \, \exists \, c' \in C_n | c = c') \wedge \\
(\forall s \in S_n \, \exists \, s' \in S_m | s = s') \wedge \\
(\forall s \in S_m \, \exists \, s' \in S_n | s = s')
\end{aligned}
$$

This yields the final rule:

$$
\begin{aligned}
F_{sem}(s,n,m) \iff & \\
& n \approx m \land \forall (n',m') \in M(s), (n,n') \in B_1 \Rightarrow (n,n') \approx (m,m') \\
& \land \forall (n',m') \in M(s), (n',n) \in B_1 \Rightarrow (n',n) \approx (m',m)
\end{aligned}
$$

Matching

- Matching is done in brute-force manner
- Multiple sets:
  - Functions that can be exactly identified
  - Functions that have multiple, possible matches
  - Functions that cannot be found via matching (no strings, no constants and no function calls - `IO_default_sync`)

- Test implementation was created
- Free as in Speech (GPLv3 or Later)
- Grab it from github: https://github.com/masterofjellyfish/findmagic
- Disclaimer: You need .NET Framework or Mono
- Supports only x86_64 for now
- Major code cleanup and more architectures (ARM, MIPS) are planned

Exact matches:

definitions	linked against	find-magic	FLIRT (IDA)
`glibc 2.21` (arch linux)	`glibc 2.21` (arch linux)	376	233
`glibc 2.21` (arch linux)	`glibc 2.13` (debian-wheezy)	105	72

- Algorithm can also provide hints
- For example: strcpy_sse2, strcpy_sse3
- Same constants, same callgraph
- Indistinguishable by the algorithm, but they do the same job
- Helpful for manual reversing!

Recovery fails if multiple matching possibilities and function is not part of unique call graph. Example:

```
.CapstoneX86Detail
    push rbp
    mov rbp, rsp
    mov rax, rdi
    add rax, 0x30
    leave
    retn
```

Pseudocode:

```
cs_x86* CapstoneX86Detail(cs_detail *detail) {
    return &detail->x86;
}
```

Questions?

Thanks!