Superset Disassembly: Statically Rewriting x86 Binaries Without Heuristics

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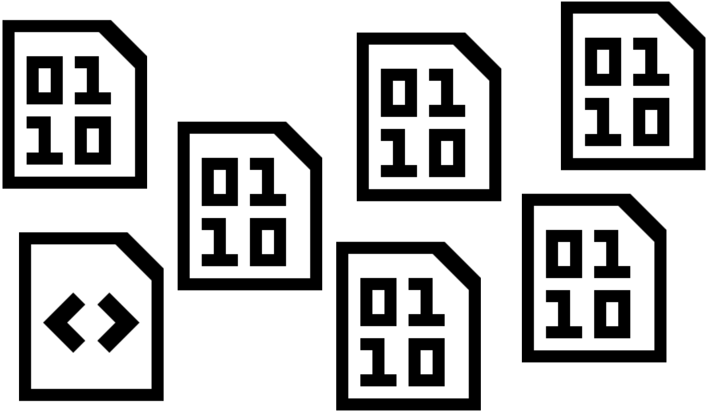
NDSS 2018

Static Binary Rewriting



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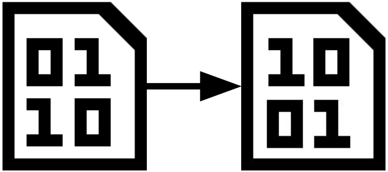

Many Static Rewriters Have Been Developed Over the Past Decades

Systems	Year	RL	DS	HS	HP	HC	HD	IN	PR	OP	HA	CF	RU
ETCH [RVL+97]	1997	✓	✓	✗	✗	✗	✗	✓	✓	✓	✗	✗	✗
SASI [ES99]	1999	✗	✗	✓	✓	✓	✓	✗	✗	✗	✓	✗	✗
PLTO [SDAL01]	2001	✗	✗	✓	✓	✓	✓	✓	✓	✓	✗	✗	✗
VULCAN [SEV01]	2001	✓	✗	✓	✓	✓	✓	✓	✓	✓	✗	✗	✗
DIABLO [PCB+05]	2005	✗	✗	✓	✓	✓	✓	✓	✓	✓	✗	✗	✗
CFI [ABEL09]	2005	✓	✗	✓	✓	✓	✓	✗	✗	✗	✓	✓	✗
XFI [EAV+06]	2006	✓	✗	✓	✓	✓	✓	✗	✗	✗	✓	✗	✗
PITTSFIELD [MM06]	2006	✗	✗	✓	✓	✓	✓	✗	✗	✗	✓	✗	✗
BIRD [NLLC06]	2006	✓	✓	✗	✓	✓	✗	✓	✓	✓	✓	✗	✗
NACL [YSD+09]	2009	✗	✗	✓	✓	✓	✓	✗	✗	✗	✓	✗	✗
PEBIL [LTCS10]	2010	✗	✗	✓	✓	✓	✓	✓	✓	✓	✗	✗	✗
SECONDWRITE [OAK+11]	2011	✓	✓	✓	✗	✗	✗	✓	✓	✓	✓	✗	✗
DYNINST [BM11]	2011	✓	✓	✗	✗	✓	✗	✓	✓	✓	✓	✓	✗
STIR/REINS [WMHL12b, WMHL12a]	2012	✓	✓	✓	✗	✗	✓	✗	✗	✗	✓	✓	✗
CCFIR [ZWC+13]	2013	✗	✓	✓	✓	✗	✗	✗	✗	✗	✓	✓	✗
BISTRO [DZX13]	2013	✓	✓	✓	✗	✗	✗	✗	✗	✗	✓	✗	✓
BINCFI [ZS13]	2013	✓	✓	✓	✓	✓	✗	✗	✗	✗	✓	✓	✗
PSI [ZQHS14]	2014	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✗
UROBOROS [WWW16]	2016	✓	✓	✗	✗	✗	✗	✓	✓	✓	✓	✓	✓
RAMBLR [WSB+17]	2017	✓	✓	✓	✗	✗	✗	✓	✓	✓	✓	✓	✓

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PLTO [SDAL01]	2001	✗	✗	✓	✓	✓	✓	✓	✓	✓	✗	✗	✗
VULCAN [SEV01]	2001	✓	✗	✓	✓	✓	✓	✓	✓	✓	✗	✗	✗
DIABLO [PCB+05]	2005	✗	✗	✓	✓	✓	✓	✓	✓	✓	✗	✗	✗
CFI [ABEL09]	2005	✓	✗	✓	✓	✓	✓	✗	✗	✗	✓	✓	✗
XFI [EAV+06]	2006	✓	✗	✓	✓	✓	✓	✗	✗	✗	✓	✗	✗
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BIRD [NLLC06]	2006	✓	✓	✗	✓	✓	✗	✓	✓	✓	✓	✗	✗
NACL [YSD+09]	2009	✗	✗	✓	✓	✓	✓	✗	✗	✗	✓	✗	✗
PEBIL [LTCS10]	2010	✗	✗	✓	✓	✓	✓	✓	✓	✓	✗	✗	✗
SECONDWRITE [OAK+11]	2011	✓	✓	✓	✗	✗	✗	✓	✓	✓	✓	✗	✗
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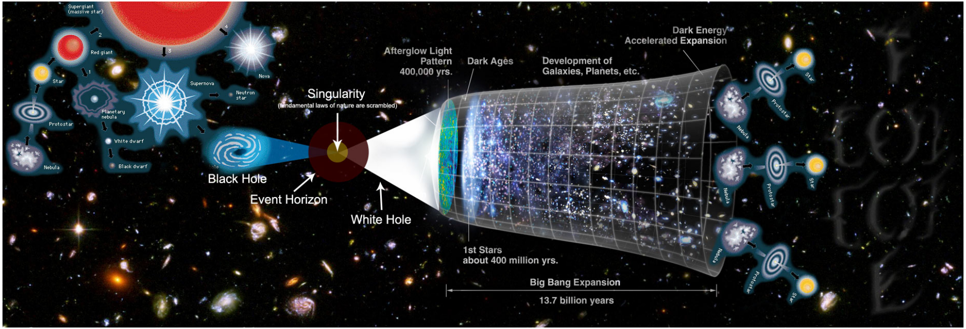
RAMBLR [WSB+17]	2017	✓	✓	✓	✗	✗	✗	✓	✓	✓	✓	✓	✓

These tools rely on various assumptions and heuristics!

MULTIVERSE: the first heuristic-free static binary rewriter



"Everything that can happen does happen." [CF12]

Fundamental Challenges

1. Recognizing and relocating static memory addresses
2. Handling dynamically computed memory addresses
3. Differentiating code and data
4. Handling function pointer arguments (e.g., callbacks)
5. Handling PIC

Working Example

```
// gcc -m32 -o sort cmp.o fstring.o sort.c
#include <stdio.h>
#include <unistd.h>

extern char *array[6];
int gt(void *, void *);
int lt(void *, void *);
char* get_fstring(int select);

void mode1(void){
    qsort(array, 5, sizeof(char*), gt);                         C4
}
void mode2(void){
    qsort(array, 5, sizeof(char*), lt);                         C4
}
                                                                C1
void (*modes[2])() = {mode1, mode2};

void main(void){
    int p = getpid() & 1;
    printf(get_fstring(0),p);
    (*modes[p])();                                              C2
    print_array();
}
```

(a) Source code of `sort.c`

Working Example

```
;nasm -f elf fstring.asm
BITS 32
GLOBAL get_fstring
SECTION .text
get_fstring:
    mov eax,[esp+4]
    cmp eax,0
    jz after
    mov eax,msg2
    ret
msg1:
    db 'mode: %d', 10, 0                C3
msg2:
    db '%s', 10, 0                      C3
after:
    mov eax,msg1
    ret
```

(b) Source code of `fstring.asm`

Working Example

```
// gcc -m32 -c -o cmp.o cmp.c -fPIC -O2
#include <stdio.h>
#include <stdlib.h>
#include <string.h>

char *array[6] = {"foo", "bar", "quuz", "baz", "flux"};                  C1
char* get_fstring(int select);

void print_array(){
    int i;
    for (i = 0; i < 5; i++){
        fprintf(stdout, get_fstring(1), array[i]);                       C5
    }
}
int lt(void *a, void *b){
    return strcmp(*(char **) a, *(char **)b);
}

int gt(void *a, void *b){
    return strcmp(*(char **) b, *(char **)a);
}
```

(c) Source code of `cmp.c`

Challenge (C)1: Recognizing and relocating static addresses

```
// gcc -m32 -o sort cmp.o fstring.o sort.c
#include <stdio.h>
#include <unistd.h>

extern char *array[6];
int gt(void *, void *);
int lt(void *, void *);
char* get_fstring(int select);

void mode1(void){
     qsort(array, 5, sizeof(char*), gt);                C4
}
void mode2(void){
     qsort(array, 5, sizeof(char*), lt);                C4
}
                                                        C1
void (*modes[2])() = {mode1, mode2};

void main(void){
     int p = getpid() & 1;
     printf(get_fstring(0),p);
     (*modes[p])();                                     C2
     print_array();
}
```

(a) Source code of `sort.c`

Challenge (C)1: Recognizing and relocating static addresses

```
Hex dump of section '.data':
  0x0804a01c 00000000 00000000 70870408 74870408 ........p...t...
  0x0804a02c 78870408 7d870408 81870408 00000000 x...}...........
  0x0804a03c f4850408 20860408                   .... ...
```

C1

(f) Hexdump of `.data` section

C1: Recognizing and relocating static memory addresses

- Data may contain function pointers
- Must identify pointers to transformed code
- Difficult to reliably distinguish pointer-like integers from pointers

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Keeping original data space intact

- No need to modify data addresses if data unchanged
- Keep read-only copy of code for inline data in original code section [OAK+11, ZS13, WMHL12b, WMHL12a]

C2: Handling dynamically computed memory addresses

```
// gcc -m32 -o sort cmp.o fstring.o sort.c
#include <stdio.h>
#include <unistd.h>

extern char *array[6];
int gt(void *, void *);
int lt(void *, void *);
char* get_fstring(int select);

void mode1(void){
      qsort(array, 5, sizeof(char*), gt);                C4
}
void mode2(void){
      qsort(array, 5, sizeof(char*), lt);                C4
}
                                                         C1
void (*modes[2])() = {mode1, mode2};

void main(void){
      int p = getpid() & 1;
      printf(get_fstring(0),p);
      (*modes[p])();                                     C2
      print_array();
}
```

(a) Source code of `sort.c`

C2: Handling dynamically computed memory addresses

```
804864c <main>:
...
8048678:    e8 73 fd ff ff          call    80483f0 <printf@plt>
804867d:    8b 44 24 1c             mov     0x1c(%esp),%eax
8048681:    8b 04 85 3c a0 04 08    mov     0x804a03c(,%eax,4),%eax
8048688:    ff d0                   call    *%eax
...
```

C2

(d) Partial binary code of sort

C2: Handling dynamically computed memory addresses

- Indirect control flow transfer (iCFT) targets computed at runtime
- May use base+offset or arbitrary arithmetic
- Difficult to predict iCFT targets statically

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Creating mapping from old code space to rewritten code space

- Do not attempt to identify original addresses to rewrite
- Ignore how address is computed; only focus on final target
- Rewrite all iCFTs to use mapping to dynamically translate address on use [PCC+04]

C3: Differentiating code and data

```
;nasm -f elf fstring.asm
BITS 32
GLOBAL get_fstring
SECTION .text
get_fstring:
    mov eax,[esp+4]
    cmp eax,0
    jz after
    mov eax,msg2
    ret
msg1:
    db 'mode: %d', 10, 0                C3
msg2:
    db '%s', 10, 0                      C3
after:
    mov eax,msg1
    ret
```

(b) Source code of `fstring.asm`

C3: Differentiating code and data

```
80485d0 <get_fstring>:
80485d0:   8b 44 24 04          mov    0x4(%esp),%eax
80485d4:   83 f8 00             cmp    $0x0,%eax
80485d7:   74 14                je     80485ed <after>
80485d9:   b8 e9 85 04 08       mov    $0x80485e9,%eax
80485de:   c3                   ret
80485df:   6d                   insl   (%dx),%es:(%edi)
80485e0:   6f                   outsl  %ds:(%esi),(%dx)
80485e1:   64 65 3a 20          fs cmp %fs:%gs:(%eax),%ah
...
```

C3

(d) Partial binary code of `sort`

C3: Differentiating code and data

- Code and data can be freely interleaved
- Found in hand-written assembly and optimizing compilers
- Linear sweep fails on inline data
- Recursive traversal lacks full coverage

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- Found in hand-written assembly and optimizing compilers
- Linear sweep fails on inline data
- Recursive traversal lacks full coverage

Brute force disassembling of all possible code

- Disassemble <u>every</u> offset [KRVV04, WZHK14, LVP+15]
- All intended code will be within resulting superset

C4: Handling function pointer arguments (e.g., callbacks)

```
// gcc -m32 -o sort cmp.o fstring.o sort.c
#include <stdio.h>
#include <unistd.h>

extern char *array[6];
int gt(void *, void *);
int lt(void *, void *);
char* get_fstring(int select);

void mode1(void){
    qsort(array, 5, sizeof(char*), gt);                    C4
}
void mode2(void){
    qsort(array, 5, sizeof(char*), lt);                    C4
}
                                                            C1
void (*modes[2])() = {mode1, mode2};

void main(void){
    int p = getpid() & 1;
    printf(get_fstring(0),p);
    (*modes[p])();                                          C2
    print_array();
}
```

(a) Source code of sort.c

C4: Handling function pointer arguments (e.g., callbacks)

```
...
80485a0 <gt>:
80485a0:   53                        push   %ebx
...
80485f4 <model>:
...
80485fa:   c7 44 24 0c a0 85 04      movl   $0x80485a0,0xc(%esp)        C4
8048601:   08
8048602:   c7 44 24 08 04 00 00      movl   $0x4,0x8(%esp)
8048609:   00
804860a:   c7 44 24 04 05 00 00      movl   $0x5,0x4(%esp)
8048611:   00
8048612:   c7 04 24 24 a0 04 08      movl   $0x804a024,(%esp)
8048619:   e8 12 fe ff ff            call   8048430 <qsort@plt>
...
```

(d) Partial binary code of `sort`

C4: Handling function pointer arguments (e.g., callbacks)

- Callbacks will fail if function pointer not updated
- Library code uses callbacks
- Difficult to identify function pointer arguments

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Rewriting all user level code including libraries

- Hard to automatically identify all function pointer arguments
- Instead, rewrite everything [ZS13]
- Use mapping (from Solution ❷) to translate callback upon use

C5: Handling PIC

```
// gcc -m32 -c -o cmp.o cmp.c -fPIC -O2
#include <stdio.h>
#include <stdlib.h>
#include <string.h>

char *array[6] = {"foo", "bar", "quuz", "baz", "flux"};     C1
char* get_fstring(int select);

void print_array(){
    int i;
    for (i = 0; i < 5; i++){
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    }
}
int lt(void *a, void *b){
    return strcmp(*(char **) a, *(char **)b);
}

int gt(void *a, void *b){
    return strcmp(*(char **) b, *(char **)a);
}
```

(c) Source code of `cmp.c`

C5: Handling PIC

```
8048510 <print_array>:
...
8048515:   53                        push   %ebx
8048516:   e8 b1 00 00 00            call   80485cc <__i686.get_pc_thunk.bx>
804851b:   81 c3 d9 1a 00 00         add    $0x1ad9,%ebx              C5
8048521:   83 ec 1c                  sub    $0x1c,%esp
8048524:   8b ab fc ff ff ff         mov    -0x4(%ebx),%ebp           C5
...
80485a0 <gt>:
80485a0:   53                        push   %ebx
...
80485cc <__i686.get_pc_thunk.bx>:
80485cc:   8b 1c 24                  mov    (%esp),%ebx               C5
80485cf:   c3                        ret
```

(d) Partial binary code of sort

C5: Handling PIC

- Position-independent code (PIC) can be loaded at arbitrary address
- Dynamically calculates relative offsets
- Offsets different for modified code

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Rewriting all `call` instructions

- For x86-32 instructions, only `call` reveals instruction pointer
- Rewrite `call` to `push`/`jmp` and push old return address [ZS13, CBG17]
- Offsets computed based on old address
- From Solution ❷, rewritten `ret` instructions translate return address with mapping

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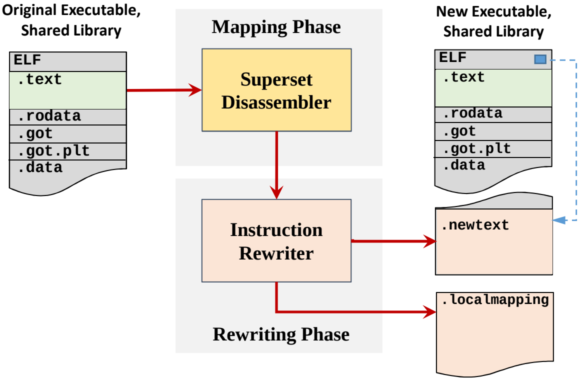

1. Mapping Phase

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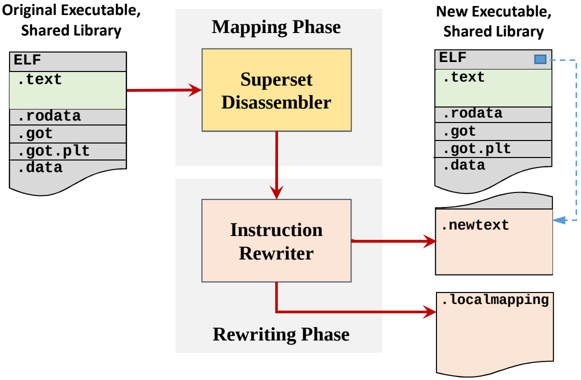

1. Mapping Phase
   - Disassemble starting from every byte

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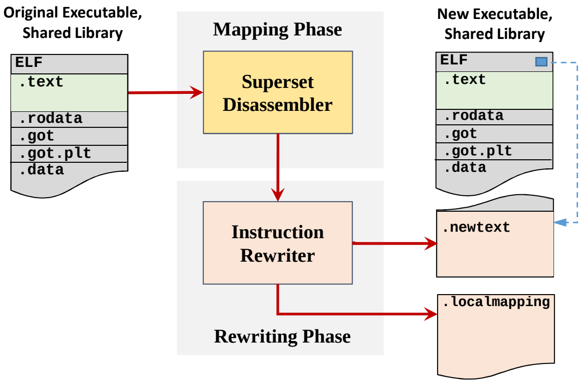

1. Mapping Phase
   - Disassemble starting from every byte
   - Determine lengths of rewritten instructions

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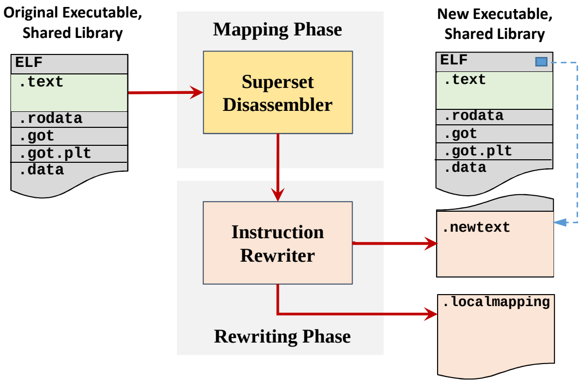
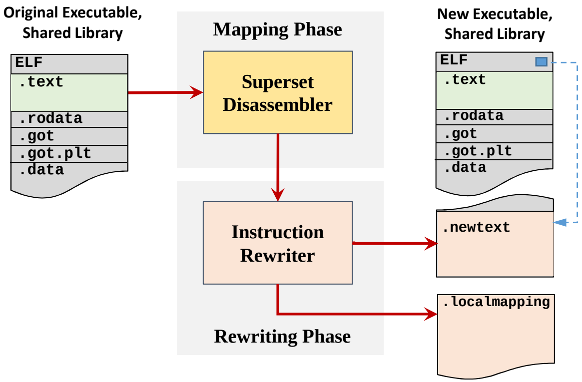


1. Mapping Phase
   - Disassemble starting from every byte
   - Determine lengths of rewritten instructions
   - Create mapping from original address to rewritten address

MULTIVERSE



1. Mapping Phase
   - Disassemble starting from every byte
   - Determine lengths of rewritten instructions
   - Create mapping from original address to rewritten address
2. Rewriting Phase

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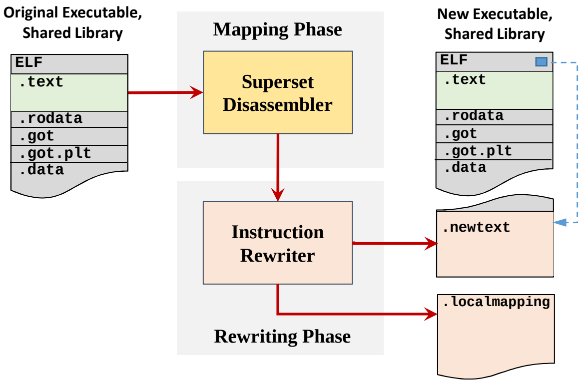

1. Mapping Phase
   - Disassemble starting from every byte
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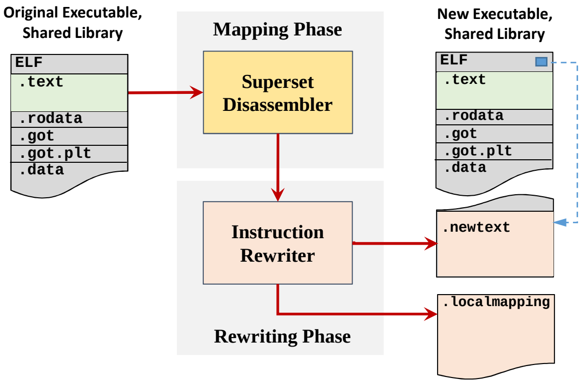
2. Rewriting Phase
   - Translate instructions to rewritten forms

MULTIVERSE



1. Mapping Phase
   - Disassemble starting from every byte
   - Determine lengths of rewritten instructions
   - Create mapping from original address to rewritten address
2. Rewriting Phase
   - Translate instructions to rewritten forms
   - Use mapping to determine final addresses

Superset Disassembly

Algorithm 1: Superset Disassembly

input : empty two-dimensional list *instructions*
input : string of raw bytes of text section *bytes*
output : all disassembled instructions are in *instructions*

for *start_offset* $\leftarrow$ *0* **to** *length(bytes)* **do**
  offset $\leftarrow$ start_offset;
  while *legal(offset) and offset* $\notin$ *instructions and offset* $<$ *length(bytes)* **do**
    instruction $\leftarrow$ disassemble(offset);
    instructions[start_offset][offset] $\leftarrow$ instruction;
    offset $\leftarrow$ offset + length(instruction);
  if *offset* $\in$ *instructions* **then**
    instructions[start_offset][offset] $\leftarrow$ "`jmp offset`";

The Algorithm

1. Start disassembly at first byte

Superset Disassembly

Algorithm 1: Superset Disassembly

```
input  : empty two-dimensional list instructions
input  : string of raw bytes of text section bytes
output : all disassembled instructions are in instructions
for start_offset ← 0 to length(bytes) do
    offset ← start_offset;
    while legal(offset) and offset ∉ instructions and
      offset < length(bytes) do
        instruction ← disassemble(offset);
        instructions[start_offset][offset] ← instruction;
        offset ← offset + length(instruction);
    if offset ∈ instructions then
        instructions[start_offset][offset] ← "jmp
         offset";
```

The Algorithm

1. Start disassembly at first byte
2. Disassemble until encounters one of:
    - Invalid instruction encoding
    - Already disassembled offset
    - End of byte sequence

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    instruction $\leftarrow$ disassemble(offset);
    instructions[start_offset][offset] $\leftarrow$ instruction;
    offset $\leftarrow$ offset + length(instruction);
  if *offset* $\in$ *instructions* **then**
    instructions[start_offset][offset] $\leftarrow$ "`jmp offset`";

The Algorithm

1. Start disassembly at first byte
2. Disassemble until encounters one of:
   - Invalid instruction encoding
   - Already disassembled offset
   - End of byte sequence
3. If offset in previous sequence, jump to the sequence

Superset Disassembly

Algorithm 1: Superset Disassembly

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input  : empty two-dimensional list instructions
input  : string of raw bytes of text section bytes
output : all disassembled instructions are in instructions
for start_offset ← 0 to length(bytes) do
    offset ← start_offset;
    while legal(offset) and offset ∉ instructions and
      offset < length(bytes) do
        instruction ← disassemble(offset);
        instructions[start_offset][offset] ← instruction;
        offset ← offset + length(instruction);
    if offset ∈ instructions then
        instructions[start_offset][offset] ← "jmp
         offset";
```

The Algorithm

1. Start disassembly at first byte
2. Disassemble until encounters one of:
   - Invalid instruction encoding
   - Already disassembled offset
   - End of byte sequence
3. If offset in previous sequence, jump to the sequence
4. If not at end of byte sequence, start disassembly from next byte

Superset Disassembly

Algorithm 1: Superset Disassembly

---

input : empty two-dimensional list *instructions*
input : string of raw bytes of text section *bytes*
output : all disassembled instructions are in *instructions*

for $start\_offset \leftarrow 0$ **to** $length(bytes)$ **do**
  offset ← start_offset;
  while $legal(offset)$ *and* $offset \notin instructions$ *and* $offset < length(bytes)$ **do**
    instruction ← disassemble(offset);
    instructions[start_offset][offset] ← instruction;
    offset ← offset + length(instruction);
  if $offset \in instructions$ **then**
    instructions[start_offset][offset] ← "`jmp offset`";

The Algorithm

1. Start disassembly at first byte
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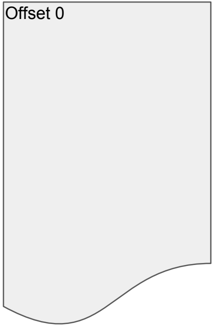
5. Go to ❷

Superset Disassembly



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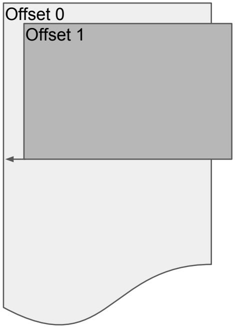

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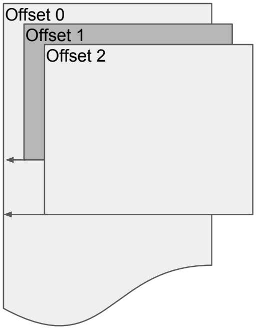

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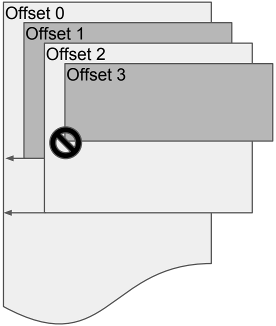

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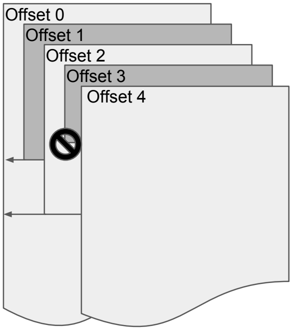

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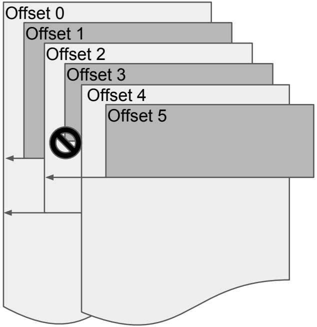

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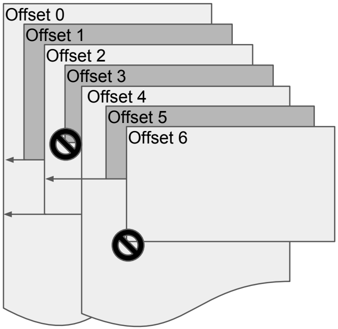

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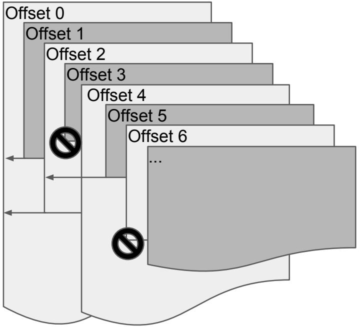
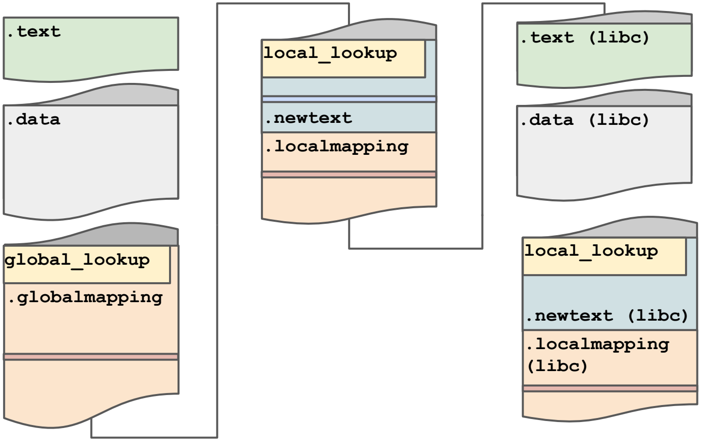


Mapping Lookups



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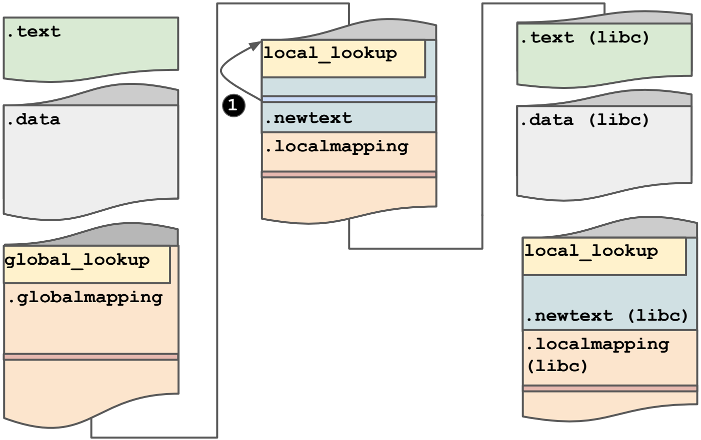

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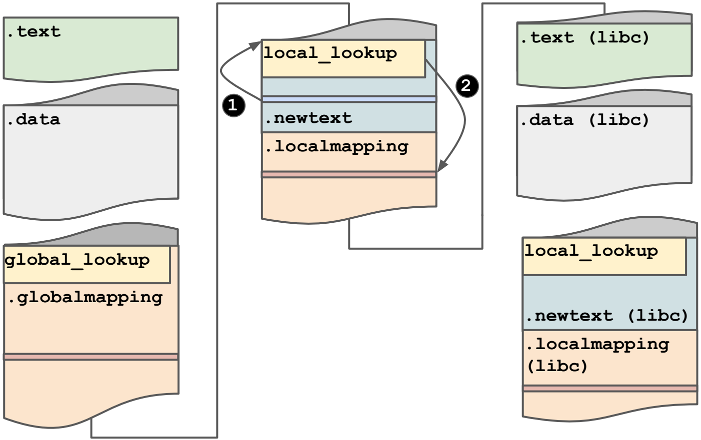

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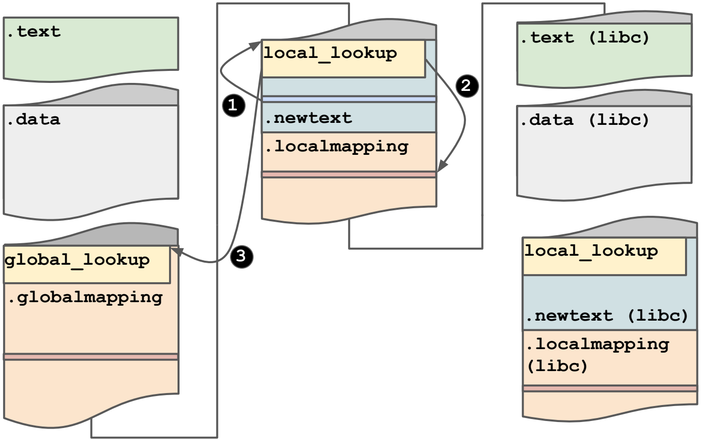

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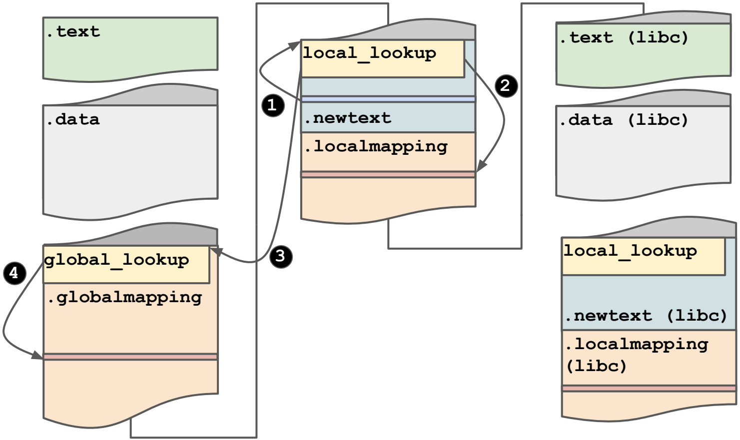

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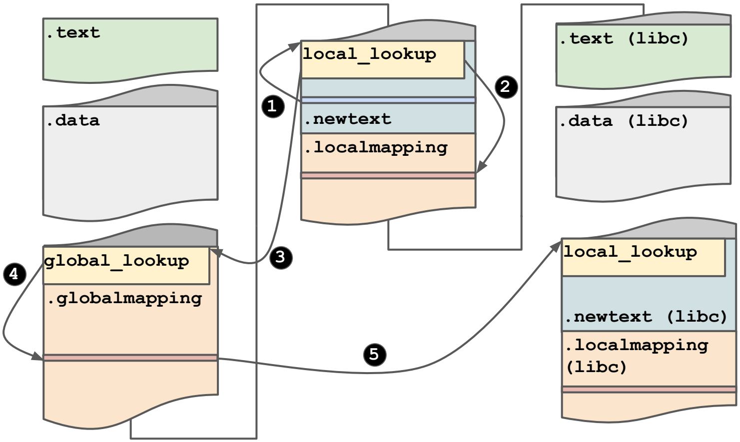

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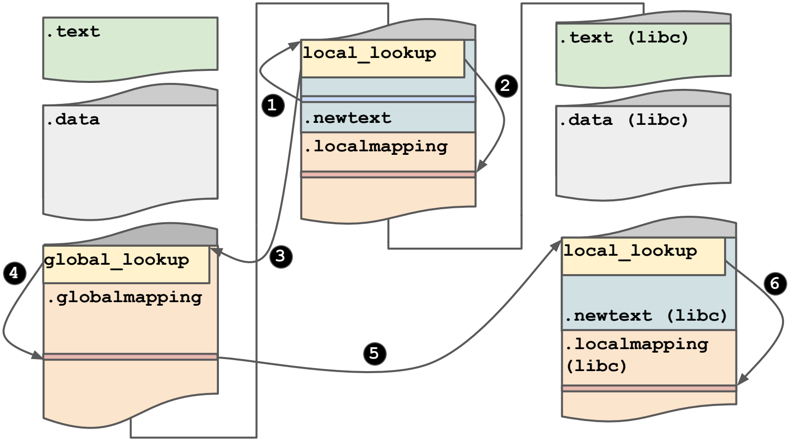

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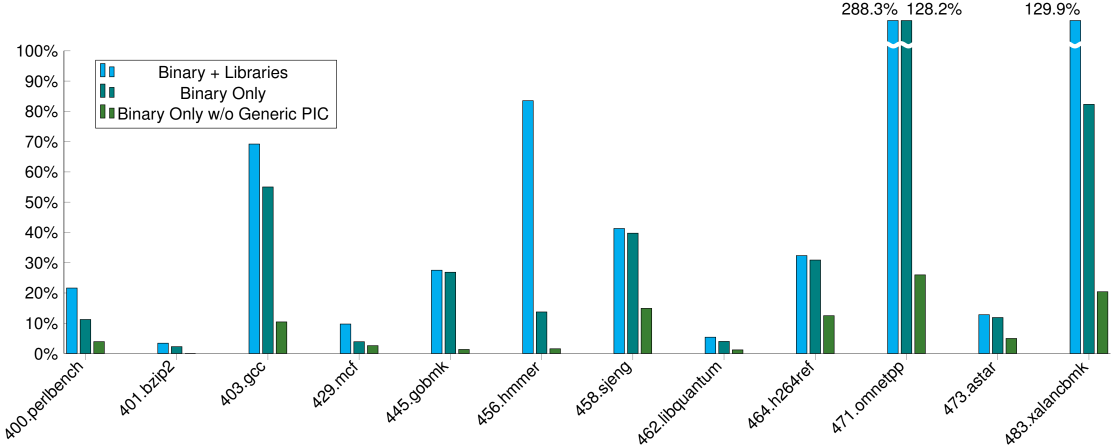
Optimization 2: No Generic PIC

- Assume only PIC is via `get_pc_thunk`
- True for many binaries
- Significant performance increase for compatible binaries

MULTIVERSE Overhead



Instrumentation Evaluation

Instruction Counting

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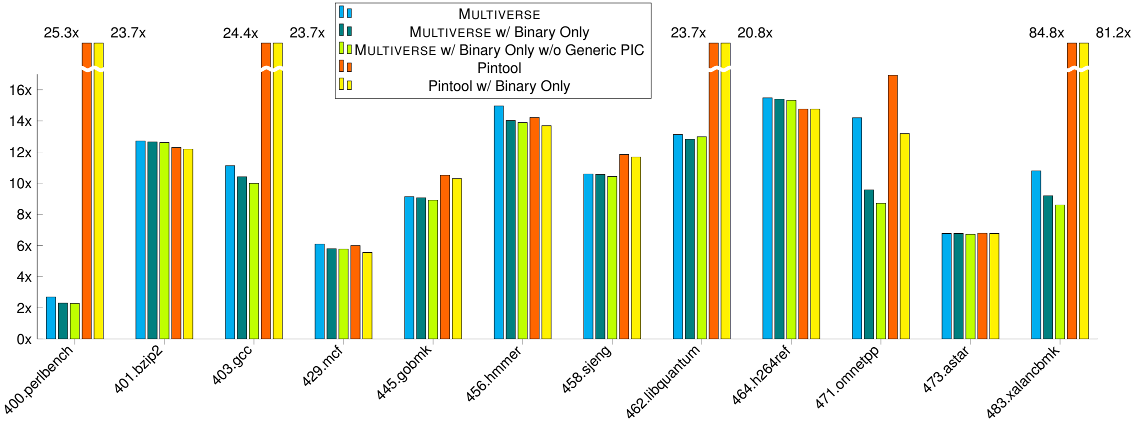

Security Applications Evaluation

Shadow Stack

- An appealing application of rewriters is binary hardening

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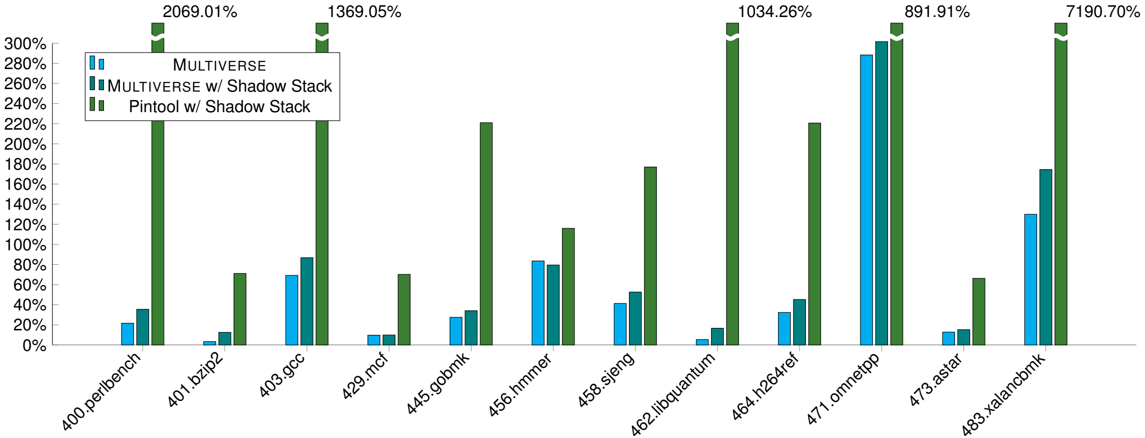
- Shadow stacks implement a form of backward-edge CFI
- Implemented a simple shadow stack in MULTIVERSE
- Compared with same type of shadow stack using PIN

Shadow Stack Overhead



Limitations and Future Work

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- MULTIVERSE now supports 64-bit applications

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- MULTIVERSE focuses on generality
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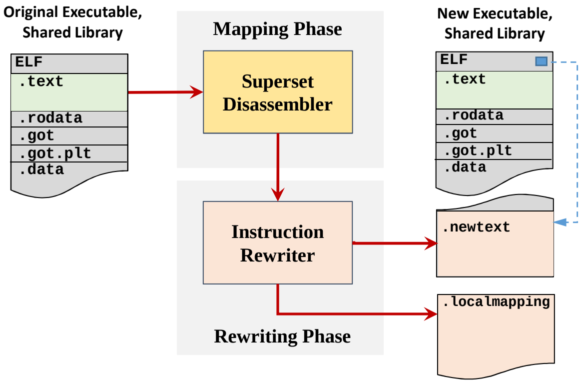
Instrumentation API

- For paper, used simple instruction-level API
- Currently working on more robust API

Conclusion



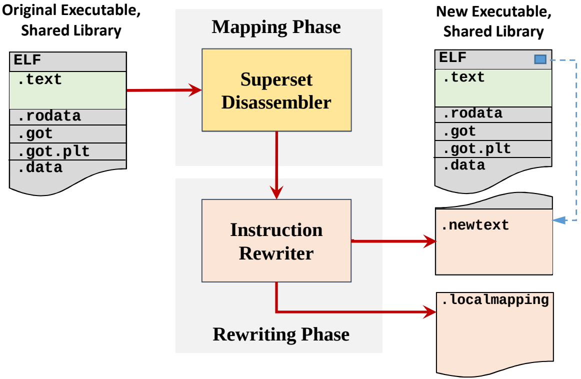
MULTIVERSE

- Heuristic-free static rewriter
- Works for x86/64 binaries
- Useful for many security applications (e.g., hardening)

MULTIVERSE Source Code

github.com/utds3lab/multiverse

Thank You



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