Advanced Topics in Malware Analysis

High Level Language Constructs In Assembly

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Function calls, If/then/else, Switch

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Learning Objectives

- Interpret high level structures in assembler
- Identify function calls
- Reconstruct switch expressions to index table of targets
- Employ loops and compiler-induced elimination of branching
- Discover arrays
- Identify structures in assembly code

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Understanding HLL Structures in ASM

Need to understand representation of compiled high-level structures in assembler

- Functions
  - Calls and Returns discussed earlier
- Control structures
  - Loops
  - Conditional branches
  - if/then/else
  - switch statements
- Data structures
  - structs/unions
  - Arrays
  - Linked structures

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IDA Annotated Function Calls

Full annotation
(PUSHed args)

```
.text:004010F3        push    10h                 ; namelen
.text:004010F5        lea     ecx, ❶[ebp+name]
.text:004010F8        push    ecx                 ; name
.text:004010F9        mov     edx, ❶[ebp+s]
.text:004010FF        push    edx                 ; s
.text:00401100        call    connect
```

Partial annotation
(MOVs)

```
.text:004011A5        mov     [esp+244h+var_23C], 10h
.text:004011AD        lea     eax, ❷[ebp+var_28]
.text:004011B0        mov     [esp+244h+var_240], eax
.text:004011B4        mov     eax, ❷[ebp+var_C]
.text:004011B7        mov     [esp+244h+var_244], eax
.text:004011BA        call    connect
```

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if/then/else

Typically an assembly sequence that:

1. Computes the expression in the if portion
2. Performs a test or cmp to ensure that CPU flags are set
3. Performs a jnz/jge/etc. and a jmp

```
    cmp [z], 5          ; if z < 5 then
    jge Else
    call func_if        ;   func_if()
    jmp After
Else:                   ; else
    call func_else ;    func_else()
After:                  ; end if
```

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Switch Case Statements

Several possible implementations:

- **Table Implementation**
  - Use a table of targets for an unconditional JMP
  - Use switch expression as index into the table of targets
  - This implementation isn't appropriate when there are numerous gaps in the case statements
  - Problem: Jump table may be embedded in the code section—problem for linear sweep disassembly
- **Tree Implementation**
  - Implements a binary search for the matching case

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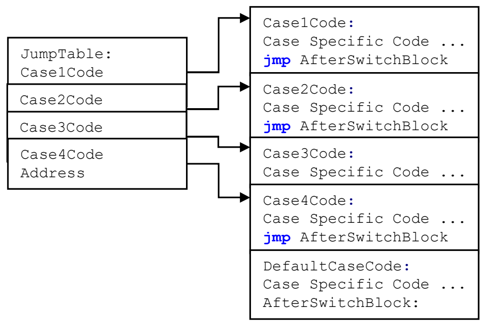
Switch: Table Implementation "Idea"

```
switch (a) {
 case 1:
   Case Specific Code ...
   break;
 case 2:
   Case Specific Code ...
   break;
 case 3: // no break!
   Case Specific Code ...
 case 4:
   Case Specific Code ...
   break;
 default:
   Case Specific Code ...
}
```

```
movzx eax, BYTE PTR [a]
sub eax, 1
cmp eax, 3
ja DefaultCaseCode
jmp DWORD PTR [JumpTable + eax * 4]
```



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Switch: Table Implementation Real Code

- Compiled with gcc on 64-bit Mac with no optimizations (i.e., -O0)

```
#include <stdio.h>
void main(void) {
  int a;
  scanf("%d", &a);
  switch (a) {
  case 0:
    puts ("Zero");
    break;
  case 1:
    puts ("One");
    break;
  case 2:
    puts ("Two");
    break;
  case 3:
    puts ("Three");
    break;
  default:
    puts("No idea.");
  }
}
```

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Switch: Table Implementation Real Code

```c
#include <stdio.h>
void main(void) {
  int a;
  scanf("%d", &a);
  switch (a) {
  case 0:
    puts ("Zero");
    break;
  case 1:
    puts ("One");
    break;
  case 2:
    puts ("Two");
    break;
  case 3:
    puts ("Three");
    break;
  default:
    puts("No idea.");
  }
}
```

```
__cstring:0000000100000F46 ; ==================================
__cstring:0000000100000F46
__cstring:0000000100000F46 ; Segment type: Pure data
__cstring:0000000100000F46 __cstring       segment byte public
__cstring:0000000100000F46                 assume cs:__cstring
__cstring:0000000100000F46                 ;org 100000F46h
__cstring:0000000100000F46 ; char aD[]
__cstring:0000000100000F46 aD              db '%d',0
__cstring:0000000100000F49 ; char aZero[]
__cstring:0000000100000F49 aZero           db 'Zero',0
__cstring:0000000100000F4E ; char aOne[]
__cstring:0000000100000F4E aOne            db 'One',0
__cstring:0000000100000F52 ; char aTwo[]
__cstring:0000000100000F52 aTwo            db 'Two',0
__cstring:0000000100000F56 ; char aThree[]
__cstring:0000000100000F56 aThree          db 'Three',0
__cstring:0000000100000F5C ; char aNoIdea_[]
__cstring:0000000100000F5C aNoIdea_        db 'No idea.',0
__cstring:0000000100000F5C __cstring       ends
__cstring:0000000100000F5C
```

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Switch: Table Implementation Real Code

```c
#include <stdio.h>
void main(void) {
  int a;
  scanf("%d", &a);
  switch (a) {
  case 0:
    puts ("Zero");
    break;
  case 1:
    puts ("One");
    break;
  case 2:
    puts ("Two");
    break;
  case 3:
    puts ("Three");
    break;
  default:
    puts("No idea.");
  }
}
```

```
                public _main
_main           proc near               ; CODE XREF: start

var_10          = qword ptr -10h
var_4           = dword ptr -4

                push    rbp
                mov     rbp, rsp
                sub     rsp, 10h
                lea     rax, [rbp+var_4]
                xor     cl, cl
                lea     rdx, aD         ; "%d"
                mov     rdi, rdx        ; char *
                mov     rsi, rax
                mov     al, cl
                call    _scanf
                mov     eax, [rbp+var_4]
                cmp     eax, 3          ; switch 4 cases
                mov     eax, eax
                mov     [rbp+var_10], rax
                ja      short loc_100000EDC ; default case
                lea     rax, off_100000EF4
                mov     rcx, [rbp+var_10]
                mov     rdx, rcx
                movsxd  rdx, dword ptr [rax+rdx*4]
                lea     rax, [rdx+rax]
                jmp     rax             ; switch jump
; ---------------------------------------------------------------
```

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Switch: Table Implementation Real Code

```c
#include <stdio.h>
void main(void) {
  int a;
  scanf("%d", &a);
  switch (a) {
  case 0:
    puts ("Zero");
    break;
  case 1:
    puts ("One");
    break;
  case 2:
    puts ("Two");
    break;
  case 3:
    puts ("Three");
    break;
  default:
    puts("No idea.");
  }
}
```

```
; ---------------------------------------------------------------------------
loc_100000EDC:                          ; CODE XREF: _main+2E↑j
                lea     rax, aNoIdea_   ; jumptable 0000000100000E96 default
                mov     rdi, rax        ; char *
                call    _puts

loc_100000EEB:                          ; CODE XREF: _main+57↑j
                                        ; _main+68↑j ...
                add     rsp, 10h
                pop     rbp
                retn
_main           endp
```

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Switch: Table Implementation Real Code

```c
#include <stdio.h>
void main(void) {
  int a;
  scanf("%d", &a);
  switch (a) {
  case 0:
    puts ("Zero");
    break;
  case 1:
    puts ("One");
    break;
  case 2:
    puts ("Two");
    break;
  case 3:
    puts ("Three");
    break;
  default:
    puts("No idea.");
  }
}
```

```
                public _main
_main           proc near               ; CODE XREF: start

var_10          = qword ptr -10h
var_4           = dword ptr -4

                push    rbp
                mov     rbp, rsp
                sub     rsp, 10h
                lea     rax, [rbp+var_4]
                xor     cl, cl
                lea     rdx, aD         ; "%d"
                mov     rdi, rdx        ; char *
                mov     rsi, rax
                mov     al, cl
                call    _scanf
                mov     eax, [rbp+var_4]
                cmp     eax, 3          ; switch 4 cases
                mov     eax, eax
                mov     [rbp+var_10], rax
                ja      short loc_100000EDC ; default case
                lea     rax, off_100000EF4
                mov     rcx, [rbp+var_10]
                mov     rdx, rcx
                movsxd  rdx, dword ptr [rax+rdx*4]
                lea     rax, [rdx+rax]
                jmp     rax             ; switch jump
; ---------------------------------------------------------------------------
```

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Switch: Table Implementation Real Code

```c
#include <stdio.h>
void main(void) {
  int a;
  scanf("%d", &a);
  switch (a) {
  case 0:
    puts ("Zero");
    break;
  case 1:
    puts ("One");
    break;
  case 2:
    puts ("Two");
    break;
  case 3:
    puts ("Three");
    break;
  default:
    puts("No idea.");
  }
}
```

```
; ---------------------------------------------------------------------------
                align 4
off_100000EF4   dd offset loc_100000E98 - 100000EF4h
                                        ; DATA XREF: _main+30↑o
                dd offset loc_100000EA9 - 100000EF4h ; jump table for switch
                dd offset loc_100000EBA - 100000EF4h
                dd offset loc_100000ECB - 100000EF4h
__text          ends
```

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Switch: Table Implementation Real Code

```c
#include <stdio.h>
void main(void) {
  int a;
  scanf("%d", &a);
  switch (a) {
  case 0:
    puts ("Zero");
    break;
  case 1:
    puts ("One");
    break;
  case 2:
    puts ("Two");
    break;
  case 3:
    puts ("Three");
    break;
  default:
    puts("No idea.");
  }
}
```

```
                public _main
_main           proc near               ; CODE XREF: start

var_10          = qword ptr -10h
var_4           = dword ptr -4

                push    rbp
                mov     rbp, rsp
                sub     rsp, 10h
                lea     rax, [rbp+var_4]
                xor     cl, cl
                lea     rdx, aD         ; "%d"
                mov     rdi, rdx        ; char *
                mov     rsi, rax
                mov     al, cl
                call    _scanf
                mov     eax, [rbp+var_4]
                cmp     eax, 3          ; switch 4 cases
                mov     eax, eax
                mov     [rbp+var_10], rax
                ja      short loc_100000EDC ; default case
                lea     rax, off_100000EF4
                mov     rcx, [rbp+var_10]
                mov     rdx, rcx
                movsxd  rdx, dword ptr [rax+rdx*4]
                lea     rax, [rdx+rax]
                jmp     rax             ; switch jump
; ---------------------------------------------------------------------------
```

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Switch: Table Implementation Real Code

```c
#include <stdio.h>
void main(void) {
  int a;
  scanf("%d", &a);
  switch (a) {
  case 0:
    puts ("Zero");
    break;
  case 1:
    puts ("One");
    break;
  case 2:
    puts ("Two");
    break;
  case 3:
    puts ("Three");
    break;
  default:
    puts("No idea.");
  }
}
```

```
loc_100000E98:                          ; CODE XREF: _main+46↑j
                                        ; DATA XREF: __text:off_100000EF4↓o
                lea     rax, aZero      ; jumptable 0000000100000E96 case 0
                mov     rdi, rax        ; char *
                call    _puts
                jmp     short loc_100000EEB
; ---------------------------------------------------------------------------
loc_100000EA9:                          ; CODE XREF: _main+46↑j
                                        ; DATA XREF: __text:off_100000EF4↓o
                lea     rax, aOne       ; jumptable 0000000100000E96 case 1
                mov     rdi, rax        ; char *
                call    _puts
                jmp     short loc_100000EEB
; ---------------------------------------------------------------------------
loc_100000EBA:                          ; CODE XREF: _main+46↑j
                                        ; DATA XREF: __text:off_100000EF4↓o
                lea     rax, aTwo       ; jumptable 0000000100000E96 case 2
                mov     rdi, rax        ; char *
                call    _puts
                jmp     short loc_100000EEB
; ---------------------------------------------------------------------------

loc_100000ECB:                          ; CODE XREF: _main+46↑j
                                        ; DATA XREF: __text:off_100000EF4↓o
                lea     rax, aThree     ; jumptable 0000000100000E96 case 3
                mov     rdi, rax        ; char *
                call    _puts
                jmp     short loc_100000EEB
; ---------------------------------------------------------------------------
loc_100000EDC:                          ; CODE XREF: _main+2E↑j
                lea     rax, aNoIdea_   ; jumptable 0000000100000E96 default
                mov     rdi, rax        ; char *
                call    _puts

loc_100000EEB:                          ; CODE XREF: _main+57↑j
                                        ; _main+68↑j ...
                add     rsp, 10h
                pop     rbp
                retn
_main           endp

; ---------------------------------------------------------------------------
                align 4
off_100000EF4   dd offset loc_100000E98 - 100000EF4h
                                        ; DATA XREF: _main+30↑o
                dd offset loc_100000EA9 - 100000EF4h ; jump table for switch
                dd offset loc_100000EBA - 100000EF4h
                dd offset loc_100000ECB - 100000EF4h
__text          ends
```

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Compiled with -O2

```c
#include <stdio.h>
void main(void) {
  int a;
  scanf("%d", &a);
  switch (a) {
  case 0:
    puts ("Zero");
    break;
  case 1:
    puts ("One");
    break;
  case 2:
    puts ("Two");
    break;
  case 3:
    puts ("Three");
    break;
  default:
    puts("No idea.");
  }
}
```

```
                lea     rdi, aD         ; "%d"
                lea     rsi, [rbp+var_4]
                xor     al, al
                call    _scanf
                mov     eax, [rbp+var_4]
                cmp     rax, 3          ; default case
                ja      short loc_100000EE0 ; jumptable 0000000100000EB1 def
                lea     rcx, off_100000EEC
                movsxd  rax, dword ptr [rcx+rax*4]
                add     rax, rcx
                jmp     rax             ; switch jump
; ---------------------------------------------------------------------------

loc_100000EB3:                          ; CODE XREF: _main+31↑j
                                        ; DATA XREF: __text:off_100000EEC↓o
                lea     rdi, aZero      ; jumptable 0000000100000EB1 case 0

loc_100000EBA:                          ; CODE XREF: _main+4C↓j
                                        ; _main+55↓j ...
                call    _puts
                add     rsp, 10h
                pop     rbp
                retn
; ---------------------------------------------------------------------------

loc_100000EC5:                          ; CODE XREF: _main+31↑j
                                        ; DATA XREF: __text:off_100000EEC↓o
                lea     rdi, aOne       ; jumptable 0000000100000EB1 case 1
                jmp     short loc_100000EBA
; ---------------------------------------------------------------------------

loc_100000ECE:                          ; CODE XREF: _main+31↑j
                                        ; DATA XREF: __text:off_100000EEC↓o
                lea     rdi, aTwo       ; jumptable 0000000100000EB1 case 2
                jmp     short loc_100000EBA
; ---------------------------------------------------------------------------

loc_100000ED7:                          ; CODE XREF: _main+31↑j
                                        ; DATA XREF: __text:off_100000EEC↓o
                lea     rdi, aThree     ; jumptable 0000000100000EB1 case 3
                jmp     short loc_100000EBA
; ---------------------------------------------------------------------------

loc_100000EE0:                          ; CODE XREF: _main+21↑j
                lea     rdi, aNoIdea_   ; jumptable 0000000100000EB1 default
                jmp     short loc_100000EBA
_main           endp

; ---------------------------------------------------------------------------
                align 4
off_100000EEC   dd offset loc_100000EB3 - 100000EECh
                                        ; DATA XREF: _main+23↑o
                dd offset loc_100000EC5 - 100000EECh ; jump table for switch
                dd offset loc_100000ECE - 100000EECh
                dd offset loc_100000ED7 - 100000EECh
```

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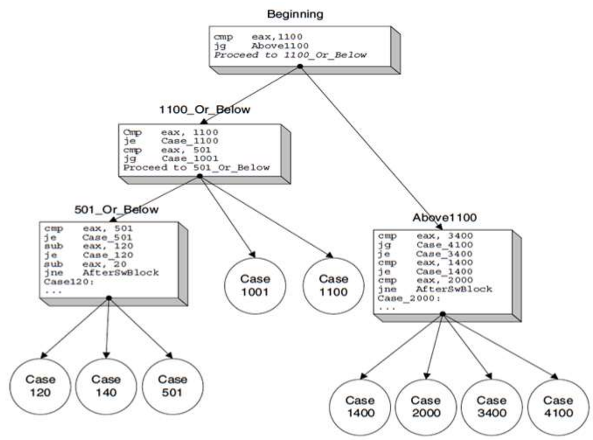
Switch: Binary Search

```
switch (value) {
  case 120: Code...
  break;
  case 140: Code...
  break;
  case 501: Code...
  break;
  case 1001: Code...
  break;
  case 1100: Code...
  break;
  case 1400: Code...
  break;
  case 2000: Code...
  break;
  case 3400: Code...
  break;
  case 4100: Code...
  break;
};
```



Source: Eilam, E. (2011). *Reversing: secrets of reverse engineering*. Hoboken, NJ: John Wiley & Sons.

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High Level Language Constructs In Assembly

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Loops

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Loops

- Loops are much as you'd expect, except…
- Pretested loops (e.g., while/do) can end up being post-tested (do/while)

```
c = 0;
while (c < 1000)
{
    array[c] = c;
    c++;
}
```

```
    mov ebx, DWORD PTR [array]
    xor ecx, ecx                        ; c = 0
Loop:                                   ; do {
    mov DWORD PTR [ebx+ecx*4], ecx        ;    array[c]=c
    add ecx, 1                            ;    c++
    cmp ecx, 1000                       ; }
    jl Loop                             ; while (c < 1000)
```

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Loops: Rep Instruction

- **rep** instruction prefix
  - Syntax: REP [INS] (INS operands)
- Repeats an instruction the number of times specified in the RCX/ECX/CX register or until the indicated condition of the ZF flag is no longer met

Repeat Prefix	Termination Condition 1	Termination Condition 2
REP	ECX=0	None
REPE/REPZ	ECX=0	ZF=0
REPNE/REPNZ	ECX=0	ZF=1

- Used to replace loops which consists of only one instruction (most often moving data)
  - To repeat a block of instructions, the LOOP instruction can be used (very rare) or a logical looping construct

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Rep Example: Libc memcpy

```
__memcpy_g_internal proc near          ; CODE XREF: __strcat_c+36↓p
                                       ; __memcpy_c+26↓p

arg_0           = dword ptr  4
arg_4           = dword ptr  8
arg_8           = dword ptr  0Ch

                push    ebp             ; save clobbered regs
                push    edi
                push    esi
                mov     eax, [esp+0Ch+arg_0] ; eax = dest
                mov     ebp, [esp+0Ch+arg_4] ; ebp = source
                mov     ecx, [esp+0Ch+arg_8] ; ecx = size
                mov     edi, eax        ; edi = dest
                mov     esi, ebp        ; esi = source
                cld                     ; direction flag = 0, inc pointer after iteration
                shr     ecx, 1          ; ecx = ecx / 2
                jnb     short loc_83879 ; jump if bit shifted off ecx was 0, otherwise ...
                movsb                   ; move 1 byte from [esi] to [edi] & inc esi and edi

loc_83879:                              ; CODE XREF: __memcpy_g_internal+16↑j
                shr     ecx, 1          ; ecx = ecx / 2
                jnb     short loc_8387F ; jump if bit shifted off ecx was 0, otherwise ...
                movsw                   ; move 1 word from [esi] to [edi] & add 2 to esi and edi

loc_8387F:                              ; CODE XREF: __memcpy_g_internal+1B↑j
                rep movsd               ; while(ecx > 0)
                                        ;   move 1 DWORD from [esi] to [edi]
                                        ;   add 4 to esi and edi
                                        ;   decrement ecx

                pop     esi
                pop     edi             ; restore saved regs
                pop     ebp
                retn                    ; return to caller
```

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Loop Unrolling

- Duplicate loop body and reduces the number of iterations
- **Goal**: Eliminate as much branching as possible at the expense of increased code size

```
int main(int argc, char* argv[])
{
    char dest[64];
    for(int i = 0; i < 64; i++)
        dest[i] = argv[1][i];
    puts(dest);
}
```

- gcc -W -Wall -Wextra -Wpedantic -O2 -S -masm=intel **-funroll-loops** fill_array.c -o fill_array.s
- Compiled on 64-bit Windows

```
main:
    push rbx ;save rbx
    sub  rsp, 96
    mov  rbx, rdx ; rbx = argv
    mov  rdx, QWORD PTR 8[rbx] ; rdx = argv[1]
    lea  rcx, 32[rsp] ; rcx = dest
    xor  eax, eax
.L2:
    movzx   r8d, BYTE PTR [rdx+rax]
    mov  BYTE PTR [rcx+rax], r8b
    movzx   r9d, BYTE PTR 1[rdx+rax]
    mov  BYTE PTR 1[rcx+rax], r9b
    movzx   r10d, BYTE PTR 2[rdx+rax]
    mov  BYTE PTR 2[rcx+rax], r10b
    movzx   r11d, BYTE PTR 3[rdx+rax]
    mov  BYTE PTR 3[rcx+rax], r11b
    movzx   ebx, BYTE PTR 4[rdx+rax]
    mov  BYTE PTR 4[rcx+rax], bl
    movzx   r8d, BYTE PTR 5[rdx+rax]
    mov  BYTE PTR 5[rcx+rax], r8b
    movzx   r9d, BYTE PTR 6[rdx+rax]
    mov  BYTE PTR 6[rcx+rax], r9b
    movzx   r10d, BYTE PTR 7[rdx+rax]
    mov  BYTE PTR 7[rcx+rax], r10b
    add  rax, 8
    cmp  rax, 64
    jne  .L2
    call puts
    xor  eax, eax
    add  rsp, 96
    pop  rbx
    ret
```

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Loop Unrolling

- **Extreme Case**: Complete unroll
  - No loop — just replicated loop body

```
int main(int argc, char* argv[])
{
    char dest[64];
    for(int i = 0; i < 64; i++)
        dest[i] = argv[1][i];
    puts(dest);
}
```

- gcc -W -Wall -Wextra -Wpedantic **-O3** -S -masm=intel fill_array.c -o fill_array.s
- Compiled on 64-bit Windows

```
main:
    push rbx ;save rbx
    sub  rsp, 96
    mov  rbx, rdx ; rbx = argv
    mov  r8, QWORD PTR 8[rbx] ; r8=argv[1]
     ; copy 64 bytes unrolled
    mov  rax, QWORD PTR [r8]
    mov  QWORD PTR 32[rsp], rax
    mov  rax, QWORD PTR 8[r8]
    mov  QWORD PTR 40[rsp], rax
    mov  rax, QWORD PTR 16[r8]
    mov  QWORD PTR 48[rsp], rax
    mov  rax, QWORD PTR 24[r8]
    mov  QWORD PTR 56[rsp], rax
    mov  rax, QWORD PTR 32[r8]
    mov  QWORD PTR 64[rsp], rax
    mov  rax, QWORD PTR 40[r8]
    mov  QWORD PTR 72[rsp], rax
    mov  rax, QWORD PTR 48[r8]
    mov  QWORD PTR 80[rsp], rax
    mov  rax, QWORD PTR 56[r8]
    mov  QWORD PTR 88[rsp], rax

    call puts
    xor  eax, eax
    add  rsp, 96
    pop  rbx
    ret
```

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Arrays

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Arrays

- Arrays indexed by a variable can generally be located easily in ASM
- Sometimes possible to determine length of array by closely analyzing code
- Arrays indexed by a constant are harder
  - Compiler will optimize
  - ASM looks like structure accesses or accesses to individual variables
- Accesses to dynamically allocated arrays are easier to deduce
  - There will generally be a call to a memory allocation function
  - Accesses to individual elements are offsets from the base address of the allocation

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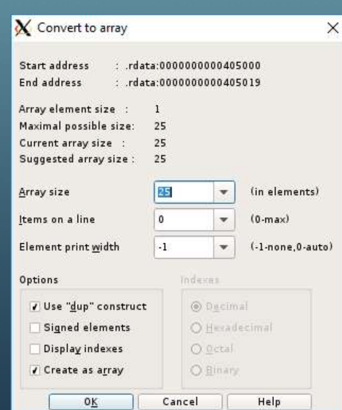
Arrays In IDA

- IDA will try to be smart about array identification
- It can miss some
  - Especially arrays of union data types!
- IDA can be coaxed into displaying arrays properly via Right-Click->Array
  - see Eagle, Chapter 8 for more



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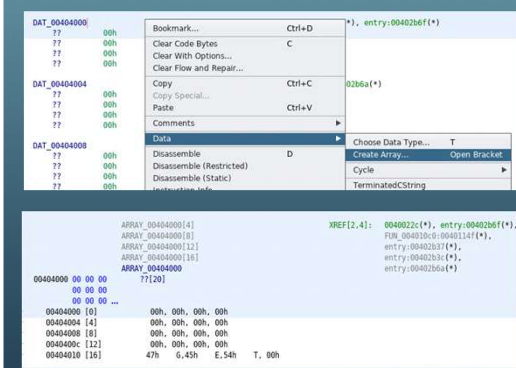
Arrays In Ghidra

- Ghidra has similar functionality
  - A little less fleshed out
- Right Click → Data → Create Array
- Then set the size in bytes



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Global Array Example

```c
int global_array[3];

int main() {
   int idx = 2;
   global_array[0] = 10;
   global_array[1] = 20;
   global_array[2] = 30;
   global_array[idx] = 40;
}
```

```
.text:00401000 _main          proc near
.text:00401000
.text:00401000 idx            = dword ptr -4
.text:00401000
.text:00401000                push    ebp
.text:00401001                mov     ebp, esp
.text:00401003                push    ecx
.text:00401004                mov     [ebp+idx], 2
.text:0040100B               ❶mov     dword_40B720, 10
.text:00401015               ❷mov     dword_40B724, 20
.text:0040101F               ❸mov     dword_40B728, 30
.text:00401029                mov     eax, [ebp+idx]
.text:0040102C               ❹mov     dword_40B720[eax*4], 40
.text:00401037                xor     eax, eax
.text:00401039                mov     esp, ebp
.text:0040103B                pop     ebp
.text:0040103C                retn
.text:0040103C _main          endp
```

Global/static array example

- (1), (2), (3) are constant accesses
- (4) is an indexed access
- Indexed access points out size of individual elements

Source: Eagle, C. (2011). *The Ida Pro Book: The unofficial guide to the worlds most popular disassembler*. San Francisco: No Starch Press.

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heap Array Example

```
int main() {
   int *heap_array = (int*)malloc(3 * sizeof(int));
   int idx = 2;
   heap_array[0] = 10;
   heap_array[1] = 20;
   heap_array[2] = 30;
   heap_array[idx] = 40;
}
```

```
.text:00401000 _main      proc near
.text:00401000
.text:00401000 heap_array      = dword ptr -8
.text:00401000 idx             = dword ptr -4
.text:00401000
.text:00401000            push    ebp
.text:00401001            mov     ebp, esp
.text:00401003            sub     esp, 8
.text:00401006           ❺push    0Ch             ; size_t
.text:00401008            call    _malloc
.text:0040100D            add     esp, 4
.text:00401010            mov     [ebp+heap_array], eax
.text:00401013            mov     [ebp+idx], 2
.text:0040101A            mov     eax, [ebp+heap_array]
.text:0040101D           ❶mov     dword ptr [eax], 10
.text:00401023            mov     ecx, [ebp+heap_array]
.text:00401026           ❷mov     dword ptr [ecx+4], 20
.text:0040102D            mov     edx, [ebp+heap_array]
.text:00401030           ❸mov     dword ptr [edx+8], 30
.text:00401037            mov     eax, [ebp+idx]

.text:0040103A            mov     ecx, [ebp+heap_array]
.text:0040103D           ❹mov     dword ptr [ecx+eax*4], 40
.text:00401044            xor     eax, eax
.text:00401046            mov     esp, ebp
.text:00401048            pop     ebp
.text:00401049            retn
.text:00401049 _main      endp
```

- Heap-allocated array
- (5) reveals size
- (1) – (4) are indexed accesses

Source: Eagle, C. (2011). *The Ida Pro Book: The unofficial guide to the worlds most popular disassembler*. San Francisco: No Starch Press.

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Struct/Union Analysis

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Struct/Union/etc.

- Field names are lost
  - Only remain with debugging symbols (which malware doesn't like)
  - Will be replaced with offsets by the compiler
- Global/static allocation:
  - Accesses to structure elements look like accesses to arrays via constant indices
- Dynamic allocation:
  - Similar to arrays, seeing memory allocation may help
- Struct / Union analysis is complicated by alignment issues!
- Good news! For common structures (e.g., struct sockaddr, etc.), IDA Pro may be able to automatically recognize struct accesses
- If recognition for particular struct types isn't available, you can add it manually in IDA

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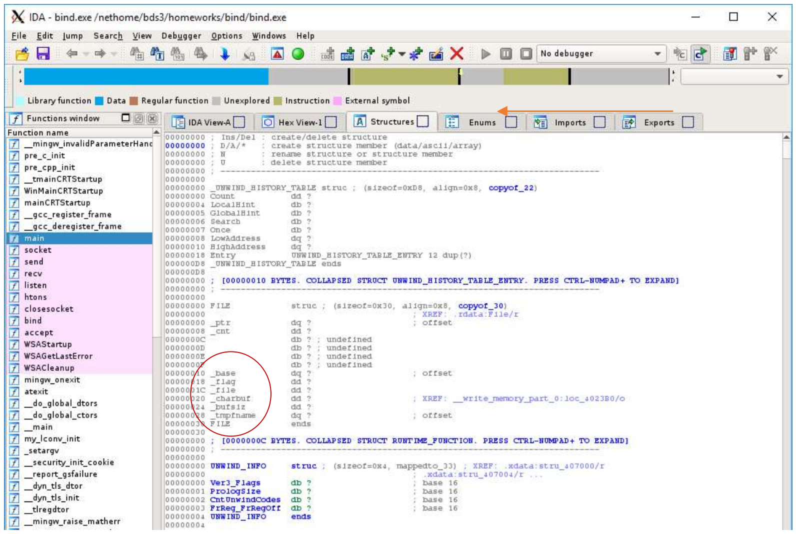
Struct/Union in ida



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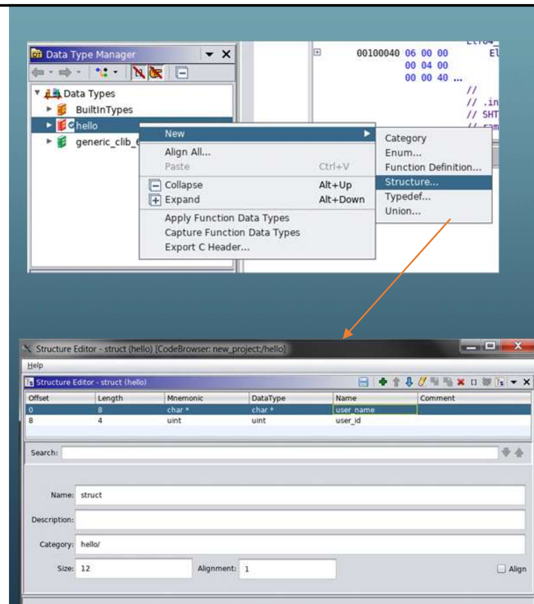
Struct/Union in Ghidra

- Ghidra does structs/unions much cleaner than IDA!
- Plus this functionality is extremely useful when paired with Ghidra's decompiler
- E.g.: If Ghidra detects a class, you can define each of its members in memory
- Makes decompiled code *significantly* more readable



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Structure Alignment Issues

- Structures defined in source code only provide field names & types
- Compilers must lay those fields out in memory
  - Different compilers/flags will choose different field alignments
- For example: A memory-efficient compilation should choose a minimal size (packed)
- But: A processor-cache-efficient compilation may choose a power of 2 alignment
- This can confuse reverse engineers --- is the extra space actually another field?

```
struct ch8_struct {    //Size      Minimum offset      Default offset
    int field1;        //  4             0                  0
    short field2;      //  2             4                  4
    char field3;       //  1             6                  6
    int field4;        //  4             7                  8
    double field5;     //  8            11                 16
};                  //Minimum total size: 19   Default size: 24
```

Source: Eagle, Chris. The IDA pro book. No Starch Press, 2011

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Global struct Example

```
struct ch8_struct global_struct;

int main() {
   global_struct.field1 = 10;
   global_struct.field2 = 20;
   global_struct.field3 = 30;
   global_struct.field4 = 40;
   global_struct.field5 = 50.0;
}
```

```
.text:00401000 _main        proc near
.text:00401000              push    ebp
.text:00401001              mov     ebp, esp
.text:00401003              mov     dword_40EA60, 10
.text:0040100D              mov     word_40EA64, 20
.text:00401016              mov     byte_40EA66, 30
.text:0040101D              mov     dword_40EA68, 40
.text:00401027              fld     ds:dbl_40B128
.text:0040102D              fstp    dbl_40EA70
.text:00401033              xor     eax, eax
.text:00401035              pop     ebp
.text:00401036              retn
.text:00401036 _main        endp
```

Global struct

- All offsets computed at compile time
- No runtime computation
- Hard to distinguish between struct and array access, except that elements of C arrays have equal size

Source: Eagle, C. (2011). *The Ida Pro Book: The unofficial guide to the worlds most popular disassembler*. San Francisco: No Starch Press.

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Heap struct Example

```
.text:00401004    ❻push  24                     ; size_t
.text:00401006     call  _malloc
.text:0040100B     add   esp, 4
.text:0040100E     mov   [ebp+heap_struct], eax
.text:00401011     mov   eax, [ebp+heap_struct]
.text:00401014    ❶mov   dword ptr [eax], 10
.text:0040101A     mov   ecx, [ebp+heap_struct]
.text:0040101D    ❷mov   word ptr [ecx+4], 20
.text:00401023     mov   edx, [ebp+heap_struct]
.text:00401026    ❸mov   byte ptr [edx+6], 30
.text:0040102A     mov   eax, [ebp+heap_struct]
.text:0040102D    ❹mov   dword ptr [eax+8], 40
.text:00401034     mov   ecx, [ebp+heap_struct]
```

Heap-allocated struct

- As for dynamically allocated arrays, size is known from malloc() call
- Next slide: struct is packed (single byte alignment)

Source: Eagle, C. (2011). *The Ida Pro Book: The unofficial guide to the worlds most popular disassembler*. San Francisco: No Starch Press.

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Same struct, but **compiler uses different alignment**

```
.text:0040100E     mov   [ebp+heap_struct], eax
.text:00401011     mov   eax, [ebp+heap_struct]
.text:00401014     mov   dword ptr [eax], 10
.text:0040101A     mov   ecx, [ebp+heap_struct]
.text:0040101D     mov   word ptr [ecx+4], 20
.text:00401023     mov   edx, [ebp+heap_struct]
.text:00401026     mov   byte ptr [edx+6], 30
.text:0040102A     mov   eax, [ebp+heap_struct]
.text:0040102D     mov   dword ptr [eax+7], 40
```

Source: Eagle, C. (2011). *The Ida Pro Book: The unofficial guide to the worlds most popular disassembler*. San Francisco: No Starch Press.

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Array of Structs, Data Structures, Oh My!

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Recall The Structure Alignment

```
struct ch8_struct {   //Size     Minimum offset     Default offset
   int field1;        //  4            0                  0
   short field2;      //  2            4                  4
   char field3;       //  1            6                  6
   int field4;        //  4            7                  8
   double field5;     //  8           11                 16
};                 //Minimum total size: 19   Default size: 24
```

Source: Eagle, C. (2011). *The Ida Pro Book: The unofficial guide to the worlds most popular disassembler*. San Francisco: No Starch Press.

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Getting tougher: Arrays of structs

```
int main() {
   int idx = 1;
   struct ch8_struct *heap_struct;
   heap_struct = (struct ch8_struct*)malloc(sizeof(struct ch8_struct) * 5);
❶  heap_struct[idx].field1 = 10;
}
```

```
.text:00401000 _main          proc near
.text:00401000
.text:00401000 idx            = dword ptr -8
.text:00401000 heap_struct    = dword ptr -4
.text:00401000
.text:00401000                push    ebp
.text:00401001                mov     ebp, esp
.text:00401003                sub     esp, 8
.text:00401006                mov     [ebp+idx], 1
.text:0040100D               ❷push    120             ; size_t
.text:0040100F                call    _malloc
.text:00401014                add     esp, 4
.text:00401017                mov     [ebp+heap_struct], eax
.text:0040101A                mov     eax, [ebp+idx]
.text:0040101D               ❸imul    eax, 24
.text:00401020                mov     ecx, [ebp+heap_struct]
.text:00401023               ❹mov     dword ptr [ecx+eax], 10
.text:0040102A                xor     eax, eax
.text:0040102C                mov     esp, ebp
.text:0040102E                pop     ebp
.text:0040102F                retn
.text:0040102F _main          endp
```

Source: Eagle, C. (2011). *The Ida Pro Book: The unofficial guide to the worlds most popular disassembler*. San Francisco: No Starch Press.

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Reverse Engineering A Linked List

- Compiled with gcc on 64-bit Windows with light optimizations (i.e., -O1)
- Recall: Windows ABI says 1st arg in RCX!

```
struct node {
  struct node *next;
  int data;
};

void print(struct node *ptr) {
  while (ptr != NULL) {
    printf("%d ", ptr->data);
    ptr = ptr->next;
  }
  printf("\n");
}
```

```
print:
    push    rsi
    push    rbx
    sub rsp, 40
    mov rbx, rcx
    test    rcx, rcx
    je  .L7
    lea rsi, .LC0[rip] ; "%d "
.L8:
    mov edx, DWORD PTR 8[rbx]
    mov rcx, rsi
    call    printf
    mov rbx, QWORD PTR [rbx]
    test    rbx, rbx
    jne .L8
.L7:
    mov ecx, 10
    call    putchar
    add rsp, 40
    pop rbx
    pop rsi
    ret
```

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Always More Complex Structures

- Trees
- Heaps
- Trees of Heaps of Stacks
- …
- C++ / object oriented languages
- Borland Delphi (!)
- Objective C is a counterexample because of rich runtime system
- Much more difficult
- Eventually, you can't identify a structure… just a collection of data blobs
- Pray for malware to be written in ASM

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Importing Shared Function

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Importing Shared Functions

- External code (i.e., libraries) can be compiled statically or dynamically
- Static is easy, you have the entire library function baked into the single binary
- Dynamic is harder, the loader needs to patch the function addresses at runtime
- Different executable formats follow different conventions

```
mov     rax, [rbp+var_10]
add     rax, 8
mov     rax, [rax]
mov     rsi, rax
mov     edi, offset format ; "Hello %s\n"
mov     eax, 0
call    _printf
```

```
; Segment type: Pure code
; Segment permissions: Read/Execute
_plt            segment para public 'CODE' use64
                assume cs:_plt
                ;org 4003F0h
                assume es:nothing, ss:nothing, ds:_data, fs:no
                dq 2 dup(?)

; int printf(const char *format, ...)
_printf         proc near               ; CODE XREF: main+2D↓p
                jmp     cs:off_601018
_printf         endp
```

```
; ===========================================================

; Segment type: Pure data
; Segment permissions: Read/Write
; Segment alignment 'qword' can not be represented in assembly
_got_plt        segment para public 'DATA' use64
                assume cs:_got_plt
                ;org 601000h
 GLOBAL OFFSET TABLE  db   ? ;
off_601018      dq offset printf        ; DATA XREF: _printf↑r
off_601020      dq offset __libc_start_main
                                        ; DATA XREF: ___libc_start_main↑r
```

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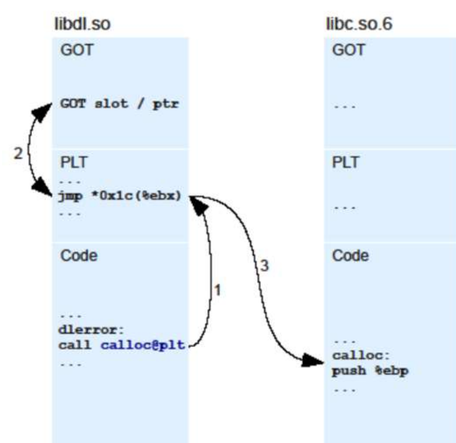
ELF Shared libraries (PLT + GOT)

- Global Offset Table
  - GOT … not Game of Thrones ☹
  - Contains pointers (**data**) to symbols imported from other shared objects (libraries)
- Procedure Linkage Table
  - PLT
  - Contains **code** that transfers control through the GOT to a symbol in the shared object
- The entries in the GOT are initialized to point to a function in the loader to resolve symbols on-the-fly
  - Before first use, all GOT entries point to loader
  - During first call, the loader executes, loads the symbol (or loads the whole library), and patches the GOT address
  - All later calls go directly to shared object



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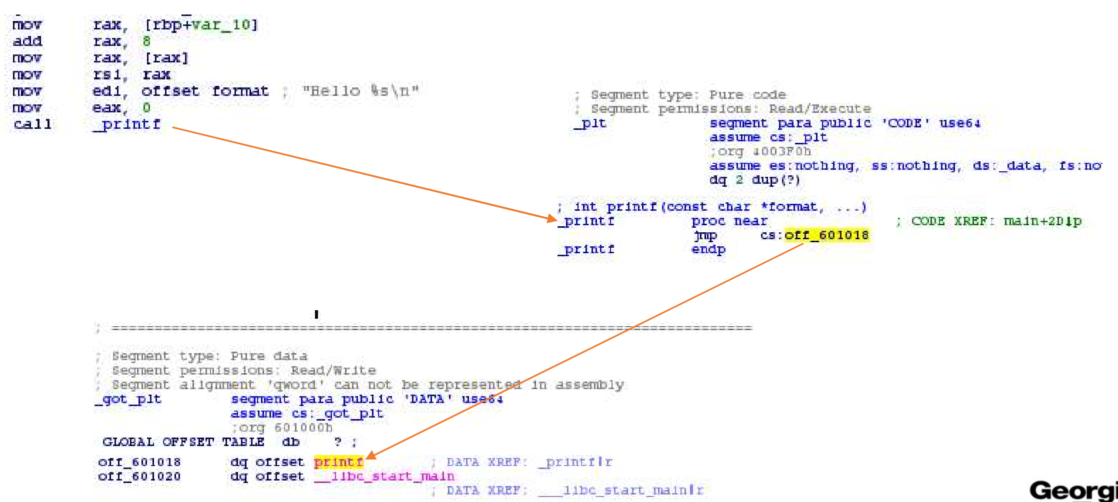
Check it out in IDA



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PE Shared libraries (IAT + .idata)

- The Windows loader is part of the OS Kernel
- The .idata section of the PE file contains
  - Import Lookup Table
    - Array of structures, each contains an ordinal or RVA of a name for each imported function
    - The ordinal represents the function’s position in the DLL’s Export Address Table
    - Structure indices are parallel to those in the Import Address Table (IAT)

- **Import Address Table** (IAT)
  - Also an array of the same structures
  - Initially both the Import Lookup Table and the IAT contain similar entries
  - The loader fills in the addresses of each imported routine in this table
- The Windows loader will proactively load some external DLLs but lazily link symbols
- Depends on how the DLL dependency was declared in the source code & how they were compiled

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PE Shared library calls: Flavor 1 of 2

- Similar to ELF, all external symbol addresses are initialized to a loader function
  - In the case of Windows this is a helper function that hands control to the kernel
  - If the DLL has been proactively loaded, it just links
  - If not, it loads the DLL and then links
- If the original source code declared an included function as external
  - Then the compiler will optimize by just directly reading the address and calling it

```
.text:000000000040165B                 mov     r8d, 0
.text:000000000040165B                 mov     edx, 1          ; protocol
.text:0000000000401660                 mov     ecx, 2
.text:0000000000401665                 mov     rax, cs:__imp_socket
.text:000000000040166C                 call    rax ; __imp_socket

.idata:0000000000409544 ; SOCKET __stdcall socket(int af, int type, int protocol)
.idata:0000000000409544                 extrn __imp_socket:qword ; DATA XREF: main+105↑r
.idata:0000000000409544                                          ; socket↑r
```

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PE Shared library calls: Flavor 2 of 2

- If the original source code **did not** declare an included function as external
  - Then the compiler will not know that it should optimize
  - Thus a stump function will be made in the .text section
    - No special section like ELF's PLT
  - All roads lead to the .idata section eventually

```
.text:00000000004015DA                 mov     rax, [rbp+640h+arg_8]
.text:00000000004015E1                 mov     rax, [rax]
.text:00000000004015E4                 mov     rdx, rax
.text:00000000004015E7                 lea     rcx, aYouCanChangeTh ; "[*] You can change this,
.text:00000000004015EE                 call    printf

.text:0000000000403240 ; =============== S U B R O U T I N E ===========================
.text:0000000000403240
.text:0000000000403240 ; Attributes: thunk
.text:0000000000403240
.text:0000000000403240 ; int printf(const char *Format, ...)
.text:0000000000403240                 public printf
.text:0000000000403240 printf          proc near               ; CODE XREF: main+6C↑p
.text:0000000000403240                                         ; main+8E↑p ...
.text:0000000000403240                 jmp     cs:__imp_printf
.text:0000000000403240 printf          endp
.text:0000000000403240

.idata:00000000004094A4 ; int printf(const char *Format, ...)
.idata:00000000004094A4                 extrn __imp_printf:qword ; DATA XREF: printf↑r
```

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Excellent additional reading (Optional)

- Symantec blogger reverse engineered the loading and linking of external symbols on Linux and Windows!
- https://www.symantec.com/connect/articles/dynamic-linking-linux-and-windows-part-one
- https://www.symantec.com/connect/articles/dynamic-linking-linux-and-windows-part-two

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Lesson Summary

- Interpret high level structures in assembler
- Identify function calls
- Reconstruct switch expressions to index table of targets
- Employ loops and compiler-induced elimination of branching
- Discover arrays
- Identify structures in assembly code

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