

Reverse Engineering

2. Analysis of a Program's Flow

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Breaking a Function into Basic Blocks

With the stack frame analyzed and local variables identified, we can start analyzing the control flow to reconstruct at first a Control Flow Graph (CFG) and later higher level constructs such as **if-then-else** and **do-while/for/while** loops.

Creating a CFG starts with breaking the code into basic blocks.

Basic Block [MIE-GEN]

Basic Block (BB) is the maximal sequence of consecutive instructions where the flow of control can only enter and can only leave the block through the first instruction and the last instruction of the block, respectively.

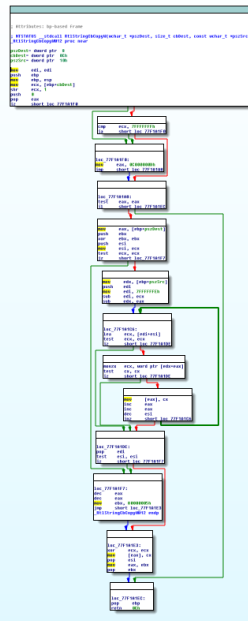
Constructing a Control Flow Graph

Once we have a function divided into basic blocks, we can construct a Control Flow Graph (CFG), where:

- each BB is a vertex;
- control flow is denoted by oriented edges between BBs.

CFG gives us an initial higher-level insight into the function being analyzed.

CFG serves as one of the inputs into a decompiler, which tries to recognize known patterns and reconstruct high-level code. Creating CFG is not always a straightforward task, especially if obfuscation techniques are used (eg. Opaque Predicates).



If-statements I

Without a CMP/TEST Instruction

This is the simplest case of a conditional jump. The statement being analyzed looks like this:

C

```
if( condition )  
    expression;
```

Assembly Pseudo Code

```
arithmetic ops calculating the condition  
jxx skip_away  
    expression  
skip_away:
```

```
77e3c798 kernel32!StringCbPrintfW  
77e3c798 mov edi, edi           // A 2-byte NOP for hot patching  
77e3c79a push ebp  
77e3c79b mov ebp, esp  
77e3c79d mov ecx, [ebp+c]       // Load 2nd parameter into ECX  
77e3c7a0 shr ecx, 1           // Unsigned divide by 2, set ZF and CF  
77e3c7a2 push 0  
77e3c7a4 pop eax  
  
// The shr instruction sets/clears ZF in EFL if the result is/isn't zero  
// Push and pop do not manipulate flags in EFL  
77e3c7a5 jz short loc_77e3c7e5  
...  
77e3c7e5 mov eax, 80070057h     // HRESULT_FROM_WIN32( ERROR_INVALID_PARAMETER )  
77e3c7ea jmp short loc_77e3c7af
```

If-statements II

With a CMP/TEST Instruction

This statement is the same as the previous one, except that it uses a `cmp` or `test` instruction to set flags in the EFL register.

C

```
if( condition )  
    expression;
```

```
77e3c798 kernel32!StringCbPrintfW
```

```
...
```

```
77e3c7a0 shr ecx, 1
```

```
77e3c7a2 push 0
```

```
77e3c7a4 pop eax
```

```
77e3c7a5 jz short loc_77e3c7e5
```

```
// The cmp instruction sets flags, based on the comparison result
```

```
77e3c7a7 cmp ecx, 7fffffffh
```

```
77e3c7ad ja short loc_77e3c7e5
```

```
...
```

```
77e3c7e5 mov eax, 80070057h // HRESULT_FROM_WIN32( ERROR_INVALID_PARAMETER )
```

```
77e3c7ea jmp short loc_77e3c7af
```

Assembly Pseudo Code

```
arithmetic ops calculating the condition  
cmp instr. sets flags based on the condition  
jxx skip_away  
    expression  
skip_away:
```

If-then-else statements

This statement is the same as the previous one, except that it adds an alternative branch.

C

```
if( condition )  
    expression1;  
else  
    expression2;
```

Assembly Code

```
77e2a8cd kernel32!UIntPtrToInt  
77e2a8cd mov edi, edi  
77e2a8cf push ebp  
77e2a8d0 mov ebp, esp  
77e2a8d2 mov eax, [ebp+8]  
77e2a8d5 cmp eax, 7fffffffh  
77e2a8da ja loc_77e5547c  
77e2a8e0 mov ecx, [ebp+c]  
77e2a8e3 mov [ecx], eax  
77e2a8e5 xor eax, eax // Fall thru  
  
77e2a8e7 loc_77e2a8e7:  
77e2a8e7 pop ebp  
77e2a8e8 retn 8  
  
77e5547c loc_77e5547c:  
77e5547c mov eax, [ebp+c]  
77e5547f or dword ptr [eax], 0fffffffh  
77e55482 mov eax, 80070216h // HRESULT_FROM_WIN32( ERROR_ARITHMETIC_OVERFLOW )  
77e55487 jmp loc_77e2a8e7 // Jump back
```

Loops I

The while loop

C

```
while( condition )  
    body;
```

Assembly Code

```
00401561  push    ebp  
00401562  mov     ebp,esp  
00401564  loc_0401564:  
00401564  mov     eax,dword ptr [ebp+c]  
00401567  movsx   ecx,byte ptr [eax]  
0040156a  test    ecx,ecx // Test the condition  
0040156c  je      loc_040158c // Jump after the loop if failed  
0040156e  mov     edx,dword ptr [ebp+8]  
00401571  mov     eax,dword ptr [ebp+c]  
00401574  mov     cl,byte ptr [eax]  
00401576  mov     byte ptr [edx],cl  
00401578  mov     edx,dword ptr [ebp+8]  
0040157b  add     edx,1  
0040157e  mov     dword ptr [ebp+8],edx  
00401581  mov     eax,dword ptr [ebp+c]  
00401584  add     eax,1  
00401587  mov     dword ptr [ebp+c],eax  
0040158a  jmp     loc_0401564 // Perform next iteration  
0040158c  loc_040158c:  
0040158c  pop     ebp  
0040158d  ret
```


Loops II

The do-while loop

C

```
do {  
    body;  
} while(condition);
```

Assembly Code

```
00401340  mov     edx,dword ptr [esp+4]  
00401344  mov     eax,dword ptr [esp+8]  
00401348  loc_0401348:  
00401348  movzx   ecx,byte ptr [eax]  
0040134b  lea     eax,[eax+1]  
0040134e  mov     byte ptr [edx],cl  
00401350  movzx   ecx,byte ptr [eax-1]  
00401354  test    cl,cl           // Test the condition  
00401356  jne     loc_0401348h    // Perform next iteration  
00401358  ret
```

Note that this function does not create a stack frame. The parameters are referred to directly using the ESP register. This approach produces a code which is both smaller and faster, but note that each push instruction changes the offset of parameters and local variables on the stack.

This omission of stack frames can be achieved at compile time by setting -fomit-frame-pointer GCC flag, or /Oy MSVC flag.

Loops III

For loop

C

```
for(
    initialization;
    condition;
    increment
)
{
    body;
}
```

Assembly Code

```
00401280  mov     ecx,dword ptr [esp+4]
00401284  xor     eax,eax
00401286  test    ecx,ecx           // Enter the loop?
00401288  jle     loc_040129c       // No - jump after it
0040128a  lea     ebx,[ebx]
00401290  loc_0401290:
00401290  mov     dword ptr [eax*4+403020h],eax
00401297  inc     eax               // Perform the increment
00401298  cmp     eax,ecx           // Test the condition
0040129a  jl      loc_0401290       // Perform next iteration
0040129c  loc_040129c:
c0040129c  ret
```

The **for** statement can be used with any part empty. This effectively allows us to construct a **while** loop by omitting both the initialization and the increment. The generated code would then be the same as in case of the **while** loop; for this reason it is not possible to determine whether the original code used **for** or **while**. The decompiler usually sticks to only one of them.

Switch I

using sub/dec

C

```
switch( arg ) {
    case 1:
        statement_1;
        break;
    case 2:
        statement_2;
        break;
    case 4:
        statement_4;
        break;
    default:
        statement_n;
        break;
}
```

Assembly Code

```
00401000 mov     eax, [ebp+8]
00401004 dec     eax
00401005 jz      short loc_401042
00401007 dec     eax
00401008 jz      short loc_401031
0040100A sub     eax, 2
0040100D jz      short loc_401020
0040100F push    offset defaultCase
00401014 call    ds:printf
0040101A add     esp, 4
0040101D xor     eax, eax           // return 0, duplicated
0040101F retn                    // Function exit, duplicated
00401020 push    offset threeParameters
00401025 call    ds:printf
0040102B add     esp, 4
0040102E xor     eax, eax           // return 0, duplicated
00401030 retn                    // Function exit, duplicated
00401031 push    offset oneParameter
00401036 call    ds:printf
0040103C add     esp, 4
0040103F xor     eax, eax           // return 0, duplicated
00401041 retn                    // Function exit, duplicated
00401042 push    offset noParameter
00401047 call    ds:printf
0040104D add     esp, 4
00401050 xor     eax, eax           // return 0, duplicated
00401052 retn                    // Function exit, duplicated
```

Switch II

using the `cmp` instruction

C

```
switch( arg ) {
    case 1:
        statement_1;
        break;
    case 2:
        statement_2;
        break;
    case 3:
        statement_3;
        break;
    case 4:
        statement_4;
        break;
    default:
        statement_n;
        break;
}
```

Assembly Code

```
8048389 mov 0x8(%ebp),%eax // Load arg. into EAX
804838c cmp $0x2,%eax
804838f je 0x80483df
8048391 jle 0x80483c0
8048393 cmp $0x3,%eax
8048396 je 0x80483b2
8048398 cmp $0x4,%eax
804839b nop
804839c lea 0x0(%esi,%eiz,1),%esi
80483a0 jne 0x80483d1
80483a2 movl $0x8048595,(%esp)
80483a9 call 0x8048350 <puts@plt>
80483ae xor %eax,%eax // Return 0;
80483b0 leave
80483b1 ret
80483b2 movl $0x8048589,(%esp)
80483b9 call 0x8048350 <puts@plt>
80483be jmp 0x80483ae
80483c0 dec %eax // Dec/sub instruction commonly used!
80483c1 jne 0x80483d1
80483c3 movl $0x8048570,(%esp)
80483ca call 0x8048350 <puts@plt>
80483cf jmp 0x80483ae
80483d1 movl $0x80485a1,(%esp)
80483d8 call 0x8048350 <puts@plt>
80483dd jmp 0x80483ae
80483df movl $0x804857e,(%esp)
80483e6 call 0x8048350 <puts@plt>
80483eb jmp 0x80483ae
```

Switch III

using a jump table

C

```
switch( arg ) {
    case 1:
        statement_1;
        break;

    case 2:
        statement_2;
        break;

    case 3:
        statement_3;
        break;

    case 4:
        statement_4;
        break;

    default:
        statement_n;
        break;
}
```

Jump Table

```
00401068 dd offset loc_401011
0040106C dd offset loc_401022
00401070 dd offset loc_401033
00401074 dd offset loc_401044
```

Assembly Code

```
00401000 mov     eax, [ebp+8]
00401004 dec     eax
00401005 cmp     eax, 3
00401008 ja      short loc_401055
0040100A jmp     ds:off_401068[eax*4] // Jump to a table item
00401011 push    offset zeroParameters
00401016 call   ds:printf
0040101C add     esp, 4
0040101F xor     eax, eax // return 0, duplicated
00401021 retn    // Function exit, duplicated
00401022 push    offset oneParameter
00401027 call   ds:printf
0040102D add     esp, 4
00401030 xor     eax, eax // return 0, duplicated
00401032 retn    // Function exit, duplicated
00401033 push    offset twoParameters
00401038 call   ds:printf
0040103E add     esp, 4
00401041 xor     eax, eax // return 0, duplicated
00401043 retn    // Function exit, duplicated
00401044 push    offset threeParameters
00401049 call   ds:printf
0040104F add     esp, 4
00401052 xor     eax, eax // return 0, duplicated
00401054 retn    // Function exit, duplicated
00401055 push    offset defaultCase
0040105A call   ds:printf
00401060 add     esp, 4
00401063 xor     eax, eax // return 0, duplicated
00401065 retn    // Function exit, duplicated
```

Summary

Now we should:

- understand the prologue and epilogue;
- understand the stack frame and its structure;
- understand what a Basic Block is;
- be able to construct a Control Flow Graph of a function, and
- understand how C constructs are compiled into assembly and be able to translate them back into a human-readable code at a higher level of abstraction.

Now, let's explore what the runtime does when a program is run. This includes:

- what the entry point is and what it does;
- calling the initializer functions;
- calling the `main` function;
- calling the terminator functions.

The Main Entry Point

The `main/wmain/_tmain` functions **are not** the real entry points. The real entry point is the function whose Relative Virtual Address (RVA) is specified in the `AddressOfEntryPoint` field in the PE optional header.

Entry point, where are you?

```
// Cast HMODULE into a pointer to the PE image start
HMODULE hSelf = GetModuleHandle(NULL); // = LoadLibrary, ...

// Image start points to MZ... - the DOS header
PIMAGE_DOS_HEADER pDosHeader = (PIMAGE_DOS_HEADER)hSelf;

// New header is located e_lfanew bytes from the start of the image
PIMAGE_NT_HEADERS32 pNTHheaders = (PIMAGE_NT_HEADERS)((BYTE*)pDosHeader + pDosHeader->e_lfanew);

// Ultimately find the entry point relative virtual address and add it the the image base
void* pfnEntryPoint = (void*)((BYTE*)pDosHeader
                             + pNTHheaders->OptionalHeader.AddressOfEntryPoint);

printf("Entry point address: %p\n", pfnEntryPoint);
```

Entry point address: 00402390

Now we should ask **who** provides the main entry point, **where is it called from**, and **why** this is not the main function?

Who calls the Main Entry Point?

We have already seen this in Lec. 1.

Entry point address: 00402390

Main entry point Call Stack

```
004136C0 Tokens.exe!main(int argc, const char* * argv) // The C entry point
00402259 Tokens.exe!__tmainCRTStartup()
0040239D Tokens.exe!mainCRTStartup() // The main entry point
75C4EE0A kernel32.dll!@BaseThreadInitThunk@12()
775A37C4 ntdll.dll!__RtlUserThreadStart@8()
775A37A3 ntdll.dll!__RtlUserThreadStart@8()
```


Who provides the main entry point?

It's the Runtime who provides the main entry point. It can be found in `crtexe.c`:

```
int mainCRTStartup( void )
{
    /*
     * The /GS security cookie must be initialized before any exception
     * handling targetting the current image is registered. No function
     * using exception handling can be called in the current image until
     * after __security_init_cookie has been called.
     */
    __security_init_cookie();
    return __tmainCRTStartup();
}
```

Notes

This function can have various names depending on the setup (whether the "Use Unicode Character Set" is specified aka. `#define UNICODE 1`) or whether `main` or `WinMain` are used. These names include:

- 1 `mainCRTStartup`
- 2 `wmainCRTStartup`
- 3 `WinMainCRTStartup`
- 4 `wWinMainCRTStartup`

__tmainCRTStartup()

Each MSVC-compiled program starts with this code:

```
__declspec(noinline) int __tmainCRTStartup( void )
{
    __try {
        ...
        // Run initializers placed into .crt$xia ... .crt$xiz segs (merged into .rdata)
        // __xi_a and __xi_z bound initializer data start and end
        // calls pre_c_init(), by default initialize C, sets default FPU mode,
        // sets the unhandled exception filter to __CxxUnhandledExceptionFilter
        if( _initterm_e( __xi_a, __xi_z ) != 0 )
            return 255;

        // Run initializers placed into .crt$xca ... .crt$xcz segs (placed into .rdata)
        // calls pre_cpp_init(), sets atexit(_RTC_Terminate), prepares parameters for main,
        // calls all constructors of static objects and registers a stub calling appropriate
        // destructors using the atexit function.
        _initterm( __xc_a, __xc_z );

        // Call whichever main function we have!
        mainret = main(argc, argv, envp);
        ...
        exit(mainret);
    }
    __except( _XcptFilter( GetExceptionCode(), GetExceptionInformation() ) ) {
        // _XcptFilter terminates, inaccessible
        mainret = GetExceptionCode();
        ExitProcess(mainret);
    }
    return mainret;
}
```

Initialization Code

The compiler can do a lot for us without involving us in runtime details. In order to use a global C++ class, all we have to do is:

A Sample Initializer Code

```
// A globally initialized class
Initializer g_InitializerClassInstance;

class Initializer {
public:
    Initializer() {
        printf("Hello pre-main code.\n");
    }

    ~Initializer() {
        printf("Hello post-main code.\n");
    }
};
```

Note: GCC uses special keywords `__attribute__((constructor))` and `__attribute__((destructor))`; this allows initializers to be used from C and get a function called during the initialization or termination phase.

Initializing the Hard Way

If we need a fine-grained control, we need to use `#pragmas`.

Fine Grained Initialization

```
#pragma section(".CRT$XIB")
__declspec(allocate(".CRT$XIB")) int (*g_MyInit_PreC)(void) = MyInit_PreC;

#pragma section(".CRT$XIY")
__declspec(allocate(".CRT$XIY")) int (*g_MyInit_PostC)(void) = MyInit_PostC;

// XCT = pre static objects constructors
// XCU = post static objects constructors
#pragma section(".CRT$XCB")
__declspec(allocate(".CRT$XCB")) void (*g_MyInit_PreCPP)(void) = MyInit_PreCPP;

#pragma section(".CRT$XCZ")
__declspec(allocate(".CRT$XCZ")) void (*g_MyInit_PostCPP)(void) = MyInit_PostCPP;
```

Initializers in `.CRT$XIxxx` sections can return a value. Returning a non-zero value causes the program initialization to abort with error 255.

Where are the Initializers? I

The `_initterm_e` and `_initterm` functions take the beginning and end pointer of a portion of the `.rdata` section of the image (following the IAT). Let's inspect this section:

Offset	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F	Ascii
00000540	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	.....
00000550	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	.....
00000610	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	.....
00000620	00	00	00	00	00	00	00	00	40	39	41	00	00	00	00	00	.....@9A.....
00000630	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	.....
00000710	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	.....
00000720	00	00	00	00	00	00	00	00	00	00	00	00	8C	10	41	00	.....I+A.....
00000730	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	.....
00000820	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	.....
00000830	C3	10	41	00	00	00	00	00	00	00	00	00	00	00	00	00	A+A.....
00000840	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	.....
00000920	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	.....
00000930	00	00	00	00	B3	11	41	00	22	11	41	00	00	00	00	00	.....3A."A.....
00000940	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	.....
00000A30	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	.....
00000A40	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	00	.....

Figure: `__xi_a` through `__xi_z` in debug version.

Each entry in this list is a pointer to a C-style initialization function:

```

413940  pre_c_init
41108c  jmp MyInit_PreC in debug, respectively MyInit_PreC in release
4110c3  jmp __atosexitinit in debug, resp. __atosexitinit in release
4111b3  jmp MyInit_PostC in debug, resp. MyInit_PostC in release
411122  jmp ___CxxSetUnhandledExceptionFilter in debug, resp. direct jump in release

```

Where are the Initializers? II

```
int _initterm_e(int (**pSegStart)(void), int (**pSegEnd)(void))
{
    int initResult = 0;
    while ( pSegStart < pSegEnd && !initResult )
    {
        if ( *pSegStart )
            initResult = (*pSegStart)();
        ++pSegStart;
    }
    return initResult;
}
```

The array holds pointers to initialization functions; if non-null, the function is called. Note that this C-initializer function aborts as soon as any initializer returns a non-zero value (unlike the C++ initializer).

Where are the Initializers? III

Offset	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F	Ascii
00000080	86	25	00	00	98	25	00	00	DE	23	00	00	FD	23	00	00	!%..!%..p#..ß#..
00000090	E8	23	00	00	86	24	00	00	00	00	00	00	00	00	00	00	e#..!\$..
000000A0	DD	12	40	00	30	10	40	00	00	10	40	00	30	10	40	00	Y:@.Q+@.H+@.Q+@.
000000B0	00	00	00	00	00	00	00	00	24	12	40	00	20	10	40	00\$!@..+@.

Figure: `__xc_a` through `__xc_z` in release version.

Each entry in this list is a pointer to a C++-style initialization function:

```

000000    -
4012dd    pre_cpp_init
401030    MyInit_PreCPP
401000    Initializer ctor stub
401020    MyInit_PostCPP

00401000    mov     ecx,4031B8h // This pointer
00401005    call    Initializer::Initializer
0040100A    push    401930h      // Address of the destructor stub
0040100F    call    atexit        // Register to be called at exit
00401014    pop     ecx          // Stack cleanup
00401015    ret

...
00401930    mov     ecx,4031B8h // This pointer
00401935    jmp     Initializer::~Initializer

```

Terminators I

As we have seen, the `atexit` API was heavily used to register stubs to call static object's destructors at the program's exit time. `Atexit` uses a dynamically allocated array pointed to by two encoded pointer globals `__onexitbegin` and `__onexitend`. Encoded function pointers are registered in this array. When the C API `exit` (but not `TerminateProcess`) is called, `atexit`-registered functions are called. Moreover, if we are using a statically linked runtime library, pre-termination and termination functions registered in `.crt$xpXXX` and `.crt$xtXXX` segments are called in the same manner as the initializers.

Terminators II

atexit code (atexit.c)

```
int __cdecl atexit(void (__cdecl *func)()) {  
    return _onexit(func) == NULL ? -1 : 0;  
}  
  
_onexit_t __cdecl _onexit(_onexit_t Func) {  
    int (__cdecl *pfnFunc)();  
  
    _lockexit();  
    pfnFunc = _onexit_nolock(Func);  
    _unlockexit();  
    return pfnFunc;  
}
```

exit code (crt0dat.c)

```
void __cdecl exit( int code ) {  
    doexit(code, 0, 0); /* full term, kill process */  
}
```

Terminators III

doexit pseudocode (crt0dat.c)

```

void __cdecl doexit(int code, int quick, int retcaller) {
    if ( !retcaller && check_managed_app() ) // If the process is managed, call CorExitProcess
        __crtCorExitProcess(uExitCode);
    ...
    if ( !quick ) {
        onexitbegin = DecodePointer(__onexitbegin); onexitend = DecodePointer(__onexitend);
        while ( 1 ) { // Iterate over all exit functions
            // Find the first "non-zero" func
            while ( --onexitend >= onexitbegin && *onexitend == EncodePointer(NULL) );
            // Ending condition
            if ( onexitend < pfn__onexitbegin ) break;
            // Decode, call, and remove the atexit registered function from the list
            pfnExitProc = (void (*)(void))DecodePointer(*onexitend);
            *onexitend = EncodePointer(0);
            pfnExitProc();
            ...
        }
        #ifndef CRTDLL
            _initterm(__xp_a, __xp_z); // Call pre-terminators
        #endif
    }
    #ifndef CRTDLL
        _initterm(__xt_a, __xt_z); // Call terminators
    #endif
    ...
    if ( ret ) return;
    if ( !ret ) __crtExitProcess(code);
}

```

Pointer Encoding

Pointers on the stack/heap could be overwritten and used to run exploit code. EncodePointer and DecodePointer APIs are used to make this difficult. These calls are internally mapped to RtlEncodePointer and RtlDecodePointer APIs in NTDLL.DLL:

```
77F1A290    db 5 dup(90h)
77F1A295 RtlEncodePointer:
77F1A295    mov edi, edi
77F1A297    push ebp
77F1A298    mov ebp, esp
77F1A29A    push ecx
77F1A29B    push 0                ; ReturnLength
77F1A29D    push 4                ; ProcessInformationLength
77F1A29F    lea eax, [ebp+ProcessInformation]
77F1A2A2    push eax              ; ProcessInformation
77F1A2A3    push 24h              ; ProcessInformationClass = process cookie
77F1A2A5    push 0FFFFFFFFh        ; ProcessHandle = GetCurrentProcess()
77F1A2A7    call _ZwQueryInformationProcess@20
77F1A2AC    test eax, eax
77F1A2AE    jl  loc_77F4276F
77F1A2B4    mov eax, [ebp+ProcessInformation]
77F1A2B7    mov cl, al
77F1A2B9    xor eax, [ebp+arg_0]
77F1A2BC    and cl, 1Fh
77F1A2BF    ror eax, cl
77F1A2C1    leave
77F1A2C2    retn 4
```

Hot Patching Support

You might have noticed there's a `mov edi,edi` instruction at the beginning of the previous function. Moreover there are 5 `nop` instructions ahead of the function start. These serve for the purpose of hot patching, a mechanism allowing us to easily replace the function at runtime without having to restart the application. The instructions above provide 7 bytes of free space which we can use to replace the function. The `mov edi,edi` instruction is replaced by a `jump short` instruction to the start of nops, where `jmp [addr]` instruction is placed. The code then looks like this:

Non-patched code

```

90  nop
90  nop
90  nop
90  nop
90  nop
function_start:
8B FF  mov edi,edi
55  push ebp
8B EC  mov ebp,esp

```

Patched code

```

jump_to_patched_function:
E9 xx xx xx xx  jmp dword ptr [&patched_function]
function_start:
EB F9  jmp short jump_to_patched_function
55  push ebp // Inaccessible
8B EC  mov ebp,esp // Inaccessible

```

Call to a jmp? I

In debug version all functions were called via an extra level of indirection. This indirection was common to all functions. What was the point of this?

```

main:
00413130 push  ebp
00413131 mov   ebp,esp
00413133 sub   esp,48h
00413136 push  ebx
00413137 push  esi
00413138 push  edi
00413139 mov   dword ptr [result],0
00413140 call PEDUMP (4110BEh)

...
PEDUMP_real:
004125F0 push  ebp
004125F1 mov   ebp,esp
004125F3 sub   esp,50h
...

_GetCurrentProcess@0:
004110B4 jmp   GetCurrentProcess (4131D0h)

___report_securityfailure:
004110B9 jmp   ___report_securityfailure (413640h)

PEDUMP:
004110BE jmp   PEDUMP_real (4125F0h)

___atosexitinit:
004110C3 jmp   ___atosexitinit (413220h)

___report_securityfailureEx:
004110C8 jmp   ___report_securityfailureEx (413750h)

__FindPESection:
004110CD jmp   __FindPESection (413FC0h)

MyInit_PreCPP:
004110D2 jmp   MyInit_PreCPP (412340h)

_LoadLibraryW@4:
004110D7 jmp   LoadLibraryW (4131EEh)

__configthreadlocale:
004110DC jmp   __configthreadlocale (4143EEh)

Initializer::Initializer:
004110E1 jmp   Initializer::Initializer (412390h)

```

Call to a jmp? II

When incremental linking is enabled, all calls in the program are made via an extra level of indirection. This allows us to **replace any function at program run-time**. New code is simply compiled, copied into the process's memory and the redirection address is updated so that it points to the new implementation. MSVC uses “Apply Code Changes”, Apple uses “Fix and Continue”, but the principle is the same.

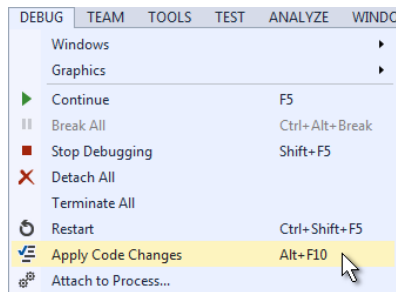


Figure: MSVC Apply Code Changes.

Import Address Table I

A module can depend on other modules. The modules depended on and symbol names and/or their ordinal numbers can be found in the Import Directory (ID) of the PE file.

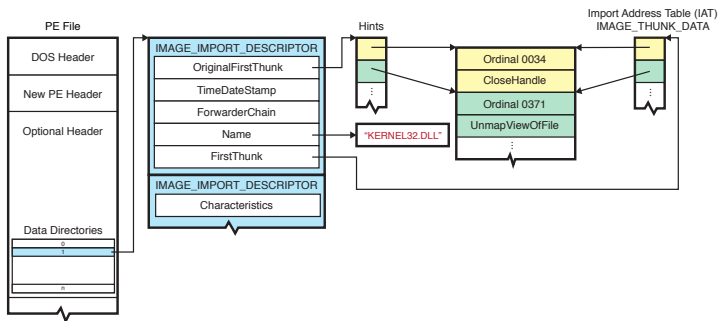


Figure: The PE Import Directory and Import Address Table.

Import Address Table II

Traversing the Import Directory

```

PIMAGE_IMPORT_DESCRIPTOR pImports = (PIMAGE_IMPORT_DESCRIPTOR)((BYTE*)pDosHeader
    + pNTHHeaders->OptionalHeader.DataDirectory[IMAGE_DIRECTORY_ENTRY_IMPORT].VirtualAddress);

PIMAGE_IMPORT_DESCRIPTOR pImportsEnd = (PIMAGE_IMPORT_DESCRIPTOR)((BYTE*)pImports
    + pNTHHeaders->OptionalHeader.DataDirectory[IMAGE_DIRECTORY_ENTRY_IMPORT].Size);

for (; pImports < pImportsEnd && pImports->OriginalFirstThunk != NULL; ++pImports)
{
    char* pszDLLName = (char*)((BYTE*)pDosHeader + pImports->Name);
    printf("DLL: %s\n", pszDLLName );

    if (pImports->Characteristics != NULL)
    {
        PIMAGE_THUNK_DATA pSymbolData = (PIMAGE_THUNK_DATA)((BYTE*)pDosHeader) + pImports->OriginalFirstThunk;

        for (; pSymbolData->u1.AddressOfData != NULL; ++pSymbolData )
        {
            // note: we should check the import type first...
            PIMAGE_IMPORT_BY_NAME pImport = (PIMAGE_IMPORT_BY_NAME)((BYTE*)pDosHeader
                + pSymbolData->u1.AddressOfData);

            printf("%04hx %s\n", pImport->Hint, pImport->Name);
        }
    }
}

```


Import Address Table III

Once an image is loaded, the loader replaces all IAT references (RVAs of `IMAGE_THUNK_DATA32` in a 32-bit PE file) (on the left) pointing to `IMAGE_IMPORT_BY_NAME` (bottom right) with real function pointers (on the right).

Offset(h)	00	01	02	03	04	05	06	07	08	09	0A	0B	0C	0D	0E	0F
00001200	8A	24	00	00	78	24	00	00	68	24	00	00	58	24	00	00
00001210	1C	27	00	00	06	27	00	00	EC	26	00	00	0A	26	00	00
00001220	BC	26	00	00	AC	26	00	00	9C	26	00	00	32	27	00	00
00001230	00	00	00	00	DC	24	00	00	E4	24	00	00	EE	24	00	00
00001240	FC	24	00	00	0A	25	00	00	22	25	00	00	3C	25	00	00
00001250	D2	24	00	00	58	25	00	00	68	25	00	00	7A	25	00	00
00001260	82	25	00	00	8A	25	00	00	9A	25	00	00	AA	25	00	00
00001270	BE	25	00	00	CC	25	00	00	D8	25	00	00	E4	25	00	00
00001280	EE	25	00	00	FA	25	00	00	10	26	00	00	2A	26	00	00
00001290	A2	26	00	00	56	26	00	00	7A	26	00	00	8C	26	00	00
000012A0	AC	24	00	00	C8	24	00	00	C0	24	00	00	B6	24	00	00
000012B0	4A	25	00	00	00	00	00	00	00	00	00	00	76	16	40	00
000012C0	30	10	40	00	00	10	40	00	30	10	40	00	00	00	00	00
000012D0	00	00	00	00	BD	15	40	00	20	10	40	00	91	14	40	00
000012E0	20	10	40	00	29	1A	40	00	00	00	00	00	00	00	00	00
000012F0	00	00	00	00	10	A2	FC	54	00	00	00	00	02	00	00	00
00001300	73	00	00	00	48	22	00	00	68	14	00	00	00	00	00	00
00001310	10	A2	FC	54	00	00	00	00	0C	00	00	00	14	00	00	00
00001320	DC	22	00	00	DC	14	00	00	48	65	6C	6C	6F	20	70	72
00001330	65	2D	6D	61	69	6E	20	63	6F	64	65	2E	0A	00	00	00

Figure: IAT on disk.

The first `IMAGE_THUNK_DATA` (4 bytes) contains a RVA of 0000248A (left). This address, when mapped into the executable's memory, points to an `IMAGE_IMPORT_BY_NAME` structure containing an ordinal number (0267) followed by a zero-terminated function name (GetModuleHandleW) (bottom right). The function is from `kernel32.dll` and resolves to address 75C4CD5C, which is written back to the IAT (right). The IAT is found in the `.rdata` section, thus it is **read-only**.

Offset(h)	00	01	02	03	04	05	06	07	08	09	0A	0B	0C	0D	0E	0F
00402000	5C	CD	C4	75	DD	2C	C4	75	62	DD	C4	75	90	CE	C4	75
00402010	C0	C4	C4	75	65	D8	C4	75	D2	C4	C4	75	D6	C5	75	
00402020	E2	7E	C4	75	10	CD	59	77	95	A2	59	77	C6	D8	C4	75
00402030	00	00	00	00	D7	ED	A5	6B	FC	ID	A5	6B	08	12	A6	6B
00402040	46	CA	A6	6B	6B	BE	A7	6B	AA	2A	A6	6B	ED	4C	AF	6B
00402050	73	22	A6	6B	5F	E2	A7	6B	CE	C7	A7	6B	93	42	A8	6B
00402060	B8	BB	AC	6B	04	A1	A8	6B	EB	35	AF	6B	E9	B9	AC	6B
00402070	86	CC	A6	6B	50	CC	A6	6B	2C	F6	B2	6B	40	F7	B2	6B
00402080	38	F6	B2	6B	B5	6B	AF	6B	0C	48	AF	6B	F7	47	AF	6B
00402090	2C	DC	A2	6B	D8	C7	A7	6B	9B	46	AF	6B	B5	C9	A7	6B
004020A0	D9	27	AD	6B	30	ED	A5	6B	E0	IC	A5	6B	FF	CB	A6	6B
004020B0	8D	BB	AC	6B	00	00	00	00	00	00	00	00	76	16	40	00
004020C0	30	10	40	00	00	10	40	00	30	10	40	00	00	00	00	00
004020D0	00	00	00	00	BD	15	40	00	20	10	40	00	91	14	40	00
004020E0	20	10	40	00	29	1A	40	00	00	00	00	00	00	00	00	00
004020F0	00	00	00	00	10	A2	FC	54	00	00	00	00	02	00	00	00
00402100	73	00	00	00	48	22	00	00	68	14	00	00	00	00	00	00
00402110	10	A2	FC	54	00	00	00	00	0C	00	00	00	14	00	00	00
00402120	DC	22	00	00	DC	14	00	00	48	65	6C	6C	6F	20	70	72
00402130	65	2D	6D	61	69	6E	20	63	6F	64	65	2E	0A	00	00	00

Figure: IAT in memory.

Offset(h)	00	01	02	03	04	05	06	07	08	09	0A	0B	0C	0D	0E	0F
00402480	6C	30	72	6F	74	65	63	74	00	00	67	02	47	65	74	4E
00402490	6F	64	75	6C	65	48	61	6E	64	6C	65	57	00	00	00	00
004024A0	52	4E	45	4C	33	32	2E	64	6C	6C	00	00	FD	06	70	72

```

iProtect...g.GetM
oduleHandleW...KE
RHEL32.dll..y.pr

```

Import Address Table IV

When an external symbol is bound, its address is resolved and all references to that symbol are updated according to the relocation table (see BIE-BEK, lec. 2). This approach is used for object files; with executables, we would have to relocate every external call during the application's startup. Instead, indirection is used and only **a single entry** per symbol is modified — the one in the IAT!

Calling a function through the IAT

```
// A function call
00401072  push  0
00401074  call  dword ptr [__imp__GetModuleHandleW@4 (402000h)]

// IAT
00402000  .dd 075C4CD5Ch      // KERNEL32.DLL!GetModuleHandleW
00402004  .dd 075C42CDDh      // KERNEL32.DLL!VirtualProtect
...
004020B0  .dd 06BACBB8Dh      // MSVCRT120.DLL!__amsg_exit
004020B4  .dd 0                // - end -

// Implementation
_GetModuleHandleWStub@4:
75C4CD5C  mov    edi,edi
75C4CD5E  push  ebp
75C4CD5F  mov    ebp,esp
```

IAT Hacking I

As we have seen, calls to the same external API are made through a single point in the program — its entry in the IAT. What happens if we change that entry in the IAT?

IAT Hacking II

As we have seen, calls to the same external API are made through a single point in the program — its entry in the IAT. What happens if we change that entry in the IAT?

All calls to that API throughout the entire program would divert!

IAT Hacking III

As we have seen, calls to the same external API are made through a single point in the program — its entry in the IAT. What happens if we change that entry in the IAT?

All calls to that API throughout the entire program would divert!

The IAT is read-only by default, but it is possible to use e.g. `VirtualProtect` to make it writable and divert all calls to that function throughout the entire program to our function.

```
BOOL WINAPI VirtualProtect(  
    LPVOID lpAddress,      // IAT_start  
    SIZE_T dwSize,         // ( IAT_size + page_size - 1 ) & ( page_size - 1 )  
    DWORD flNewProtect,    // PAGE_READWRITE  
    PDWORD lpflOldProtect  
);
```

IAT Hacking IV

Can we get beyond our process boundary? The answer is a definite YES. We can either use functions such as VirtualAllocEx, ReadProcessMemory, WriteProcessMemory, VirtualProtectEx, CreateRemoteThread to hack another process(es) and to inject code/DLL into them, or use the Native API!

Win32 API

```
BOOL WINAPI VirtualProtectEx(  
    _In_ HANDLE hProcess,  
    _In_ LPVOID lpAddress,  
    _In_ SIZE_T dwSize,  
    _In_ DWORD flNewProtect,  
    _Out_ PDWORD lpflOldProtect  
);
```

NT API

```
NTSTATUS NTAPI  
NtProtectVirtualMemory(  
    IN HANDLE ProcessHandle,  
    IN OUT PVOID *BaseAddress,  
    IN OUT PULONG NumOfBytesToProtect,  
    IN ULONG NewAccessProtection,  
    OUT PULONG OldAccessProtection  
);
```

Bibliography



Russinovich M., Solomon D. A., Ionescu A.: *Windows Internals Part 1*, 6th ed., 2012.



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