Special Topics in Security
ECE 5698

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Low-Level Essentials for Understanding Security Problems

Computer Architecture

- The modern computer architecture is based on “Von Neuman”
  - Two main parts: CPU (Central Processing Unit) and Memory
  - This architecture is used everywhere (e.g., even mobile phones)
  - This architecture is fundamental, has not changed yet
- What is memory used for?
  - E.g., location of curser, size of windows, shape of each letter being displayed, graphics of icons, text, values, etc…
  - Von Neuman also says that not only data, but programs should also be in main memory

The CPU

- Storing data by itself, of course, is not enough
  - The CPU reads instructions from memory one by one
    - Executes them (*fetch-execute-cycle*)
- Following components make up the CPU
  - Program Counter
  - Instruction Decoder
  - Data bus
  - General-purpose registers
  - Arithmetic and logic unit

Program Counter and Instruction Decoder

- Is used to tell the CPU where to fetch next instruction
  - There is no difference between memory and data
  - Program counter holds memory address of next instruction
- The instruction decoder then makes sense of the instruction
  - Addition? Substraction? Multiplication? Move operation? Etc.
  - A typical instruction usually consists of memory locations as well
    - E.g., move this piece of data from memory address X to memory address Y

The Data Bus and Registers

- The data bus connects the memory and the CPU
  - i.e., it is the actual, physical wire
- In addition to the memory, the processor has high-speed, special memory location
  - Called *registers*
    - Special-purpose registers
    - General-purpose registers
    - Registers are used for computation

Arithmetic and Logic Unit

- Once instruction has been decoded, CPU passes data and decoded instruction to ALU
  - Now, the instruction is actually executed
  - Results of the computation are placed on the data bus and sent to memory locations given in the instruction
  - For example, we can tell ALU to add 1 to register A and place result in register B

Some basics (you know them ;))

- The number attached to each storage location
  - … is an *address*
  - A single storage location is called a *byte*
  - On x86 processors, a byte is between 0..255
  - Obviously, two bytes can be used to represent any number between 0..65536
  - Four bytes can be used to represent numbers between 0..4294967295., Luckily, we do not have to worry about this. The architecture helps us to do math with 4 byte numbers
- Addresses sizes are in *words* (a word is 4 bytes)
  - Note that this means that a number and an address are dealt with the same way

Data Accessing Methods

- Processors have a number of different ways of accessing data
  - Known as *addressing modes*
  - The simplest method is known as *immediate mode*
    - Data access is enabled in instruction itself
  - In *register addressing mode* the instruction contains a register to access rather than memory location
  - In *direct addressing mode,* the instruction contains memory address
  - In *indexed addressing mode*, the instruction contains memory address to access and an index register to offset
    - E.g., Address 1000, register=4, address=1004

Data Accessing Methods

- Processors have a number of different ways of accessing data
  - Indirect addressing mode
    - We take address that is stored in register
  - Base point addressing mode
    - You take address in register and add an offset
    - Used a lot

A Simple Program in Assembler

```
# No INPUT
# Returns a status code, you can view it by typing echo $?
# %ebx holds the return code
.section .data
.section .text
.globl _start

_start:
mov $1, %eax # This is the sys call for exiting program
movl $0, %ebx # This value is returned as status
int $0x80 # This interrupt calls the kernel, to execute sys call
```

So now we have the source code…

- So how do we create the application?
  - Well, we need to assemble and link the code
  - This can be done by using the assembler *as:*
    - *as exit.s –o exit.o*
    - *ld –o exit exit.o*

Anatomy of the Code

- .section breaks up the program into sections
  - .data, obviously, is used for variables and data you might need
  - .text is the code of the program that you write
  - .globl _start indicates that _start is a symbol, required by the linker
  - _start, in fact, indicates that the loader will load and start the program from this location
  - The next instruction, *movl,* has two operands: *source* and *destination*
    - *movl, addl, subl*

Registers on the x86 Architecture

- General purpose registers:
  - %eax, %ebx, %ecx, %edx, %edi, %esi
- Special purpose registers:
  - %ebp, %esp, %eip, %eflags
- Some registers (e.g., %eip, %eflags) can only be accessed through special instructions
- The $ sign before a number means that we are using *immediate addressing mode*

Let us write a more complicated Program

- Task: Find the maximum of a list of numbers
  - Questions to ask:
    - Where will the numbers be stored?
    - How do we find the maximum number?
    - How much storage do we need?
    - Will registers be enough or is memory needed?
  - Let us designate registers for the task at hand:
    - %edi holds position in list
    - %ebx will hold current highest
    - %eax will hold current element examined

“Algorithm” we use

- Check if %eax is zero (i.e., termination sign)
  - If yes, exit
  - If not, increase current position %edi
  - Load next value in the list to %eax
    - We need to think about what addressing mode to use here
  - Compare %eax (the current value) with highest value so far %ebx
  - If the current value is higher, replace %ebx
  - Repeat until termination

Let's get down to the code

```
.section .data
        data_items:
        .long 3,67,34,222,45,75,54,34,44,33,22,11,66,0
.section .text
.globl _start
_start:
mov $0, %edi # Reset index
movl data_items(,%edi,4), %eax
movl %eax, %ebx #First item is the biggest so far
start_loop:
cmpl $0, %eax
je loop_exit
```

Let’s get down to the code

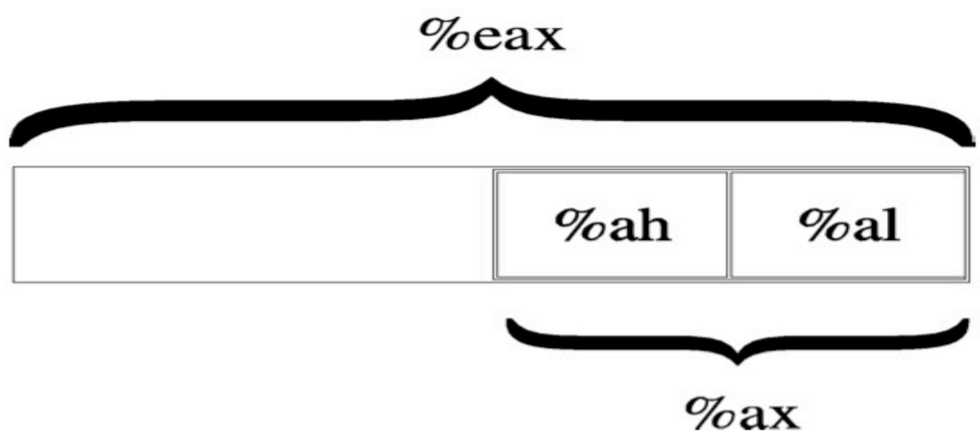
```
incl %edi # Increment edi
movl data_items(,%edi,4), %eax #load the next value
cmpl %ebx, %eax # Compare ebx with eax
jle start_loop # if it is less, then just jump to the beginning
movl %eax, %ebx  #Otherwise, store the new largest number
jmp start_loop

loop_exit:
movl $1, %eax # Remember the exit sys call? It is 1
int $0x80
```

Important Instruction

- The compare instruction
  - cmpl $0, %eax
  - je end_loop
  - Other jump instructions *jg, jge, jl, jle, jmp*
- mov instruction
  - Used often. One of the most important and common instructions that you are going to see
    - … and use, for example, when writing shell code

What if we do not want to move a word?

- Suppose you only need to move a *byte* at a time, not a word
  - You can use the *movb* instruction
  - In %eax, the least significant half is addressed by %ax (i.e., 2 bytes)
  - %ax is divided into %ah and %al (1 byte in size)



Functions

- A function is composed of several different pieces
  - function name
    - Symbol that represents where the function starts
  - function parameters
    - Data items passed to function for processing
  - Local variables
    - Temporary storage areas used in the function
    - Thrown away when the processing finishes
  - Static variables
    - Storage area that is reused over invocations
  - Global variables
    - Storage areas outside the function

The Return Address

- The return address is a parameter that tells the function where to resume executing after the function is completed
  - It is “invisible” – the programmer does not necessarily know the address
  - When a function is invoked, the calling point is saved
  - When the function completes, it returns to the initial calling point
  - In machine code, functions are called with *call* and they return when they execute *ret*
- Return value
  - Usually, a single value is returned to caller

The Calling Convention

- The way that the variables are stored and the parameters and return values are transferred by the computer varies from language to language as well
  - This variance is known as a language's *calling convention*
- The assembly language can use any calling convention
  - You can make one up yourself… however…
  - If you want to interoperate with other languages, you need to follow their calling conventions
    - e.g., suppose you want your code to be callable from a C program…

The Stack

- Each computer program that runs uses a region of memory called the stack to enable functions to work properly
  - You generally keep the things that you are working on toward the top, and you take things off as you are finished working with them
- The computer's stack lives at the very top addresses of memory
  - You can push values onto stack using *pushl*
  - You can retrieve items from the stack using *popl*

The Stack

- Where is the “top” of the stack
  – Because of architectural considerations, the computer stack grows from higher addresses to lower addresses
  – i.e., it grows downwards
  – How do we know where the “top” of the stack is?
    - The %esp register stores a pointer to stack location
  – If something is pushed onto stack, the stack decreases by %esp – 4 if *pushl* is used
  – Yes, but if I only want to read? How can I do this without popping?
    - movl (%esp), %eax
    - movl 4(%esp), %eax (for addressing a higher value)

The C calling convention

- The stack is the key element for implementing a function's…
  - local variables, parameters, and return address
  - Before executing a function, a program pushes all of the parameters for the function onto the stack in the reverse order that they are documented
  - Program issues *call* instruction
  - *call* does two things
    - pushes address of next instruction (i.e., return)
    - Modifies %eip to point to function start

The C calling convention

- Parameter #N

  …

  Parameter 2

  Parameter 1

  Return Address <--- (%esp)

- Now, function has to do some thing
  - It saves the current base pointer register %ebp
    - Needed for local variables and parameters
  - pushl %ebp
  - movl %esp, %ebp

The C calling convention

- Copying the stack pointer into the base pointer at the beginning of a function allows you to always know where your parameters are

Parameter #N <--- N*4+4(%ebp)

...

Parameter 2 <--- 12(%ebp)

Parameter 1 <--- 8(%ebp)

Return Address <--- 4(%ebp)

Old %ebp <--- (%esp) and (%ebp)

The C calling convention

- *stack frame* consists of all of the stack variables used within a function
- Next, the function reserves space on the stack for any local variables it needs
  - This is done by simply moving the stack pointer out of the way
  - E.g., if we need two words: *subl $8, %esp*
  - Variables are local because when function returns, the stack frame is reset and variables disappear

The C calling convention

- Our stack now looks like this:
  - Parameter #N <--- N*4+4(%ebp)
    ...
    Parameter 2 <--- 12(%ebp)
    Parameter 1 <--- 8(%ebp)
    Return Address <--- 4(%ebp)
    Old %ebp <--- (%ebp)
    Local Variable 1 <--- -4(%ebp)
    Local Variable 2 <--- -8(%ebp) and (%esp)

The C calling convention

- Now we can use the %ebp for accessing all variables
  - %ebp was specifically designed for this purpose
- When a function is done…
  - It stores its return value in %eax
  - It resets the stack to what it was when it was called
    - It gets rid of the current stack frame and puts the stack frame of the calling code back into effect
  - It returns by invoking the *ret* command
  - movl %ebp, %esp

    popl %ebp

    ret

Buffer Overflows

Buffer Overflows

- A buffer overflow occurs any time the program attempts to store data beyond the boundaries of a buffer, overwriting the adjacent memory locations
  - Results from mistakes while writing the code
  - Unfamiliarity with the language
  - Ignorance about security issues
  - Unwillingness to take any extra effort
- Vulnerable software
  - Mostly C/C++ programs
  - Not language with automated memory management
    - Java, Perl, Python, C#

Buffer Overflows

- Common targets
  - setuid/setgid programs
  - network servers

- Goals
  - Overwrite other “interesting” variables
    (file names, passwords, pointers...)
  - Force the program to execute operations it was not intended to do:
    - inject (or simply find) code into the process memory
    - change flow of control (flow of execution) to execute that code

Buffer Overflows

- Morris worm (1988): overflow in fingerd
  - 6,000 machines infected (10% of the Internet)
- CodeRed (2001): overflow in MS-IIS server
  - 300,000 machines infected in 14 hours
- SQL Slammer (2003): overflow in MS-SQL server
  - 75,000 machines infected in **10 minutes**
- In 2003, around 75% of the vulnerabilities were buffer overflows (CERT)

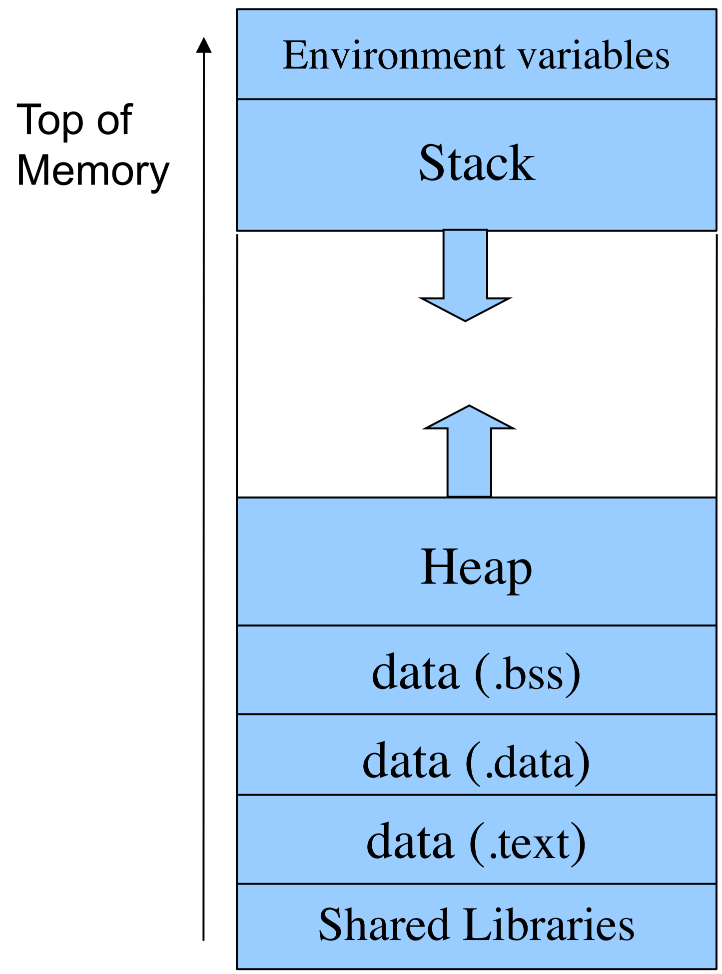
  Why are they still interesting and important?

Part I
A deeper look into the STACK

Memory Layout

- Stack segment
  - local variables
  - procedure activation records
- Data segment
  - global uninitialized variables (.bss)
  - global initialized variables (.data)
  - dynamic variables (heap)
- Code (Text) segment
  - program instructions
  - usually read-only
- In linux, under the proc filesystem

  >cat /proc/<pid>/maps



The Stack

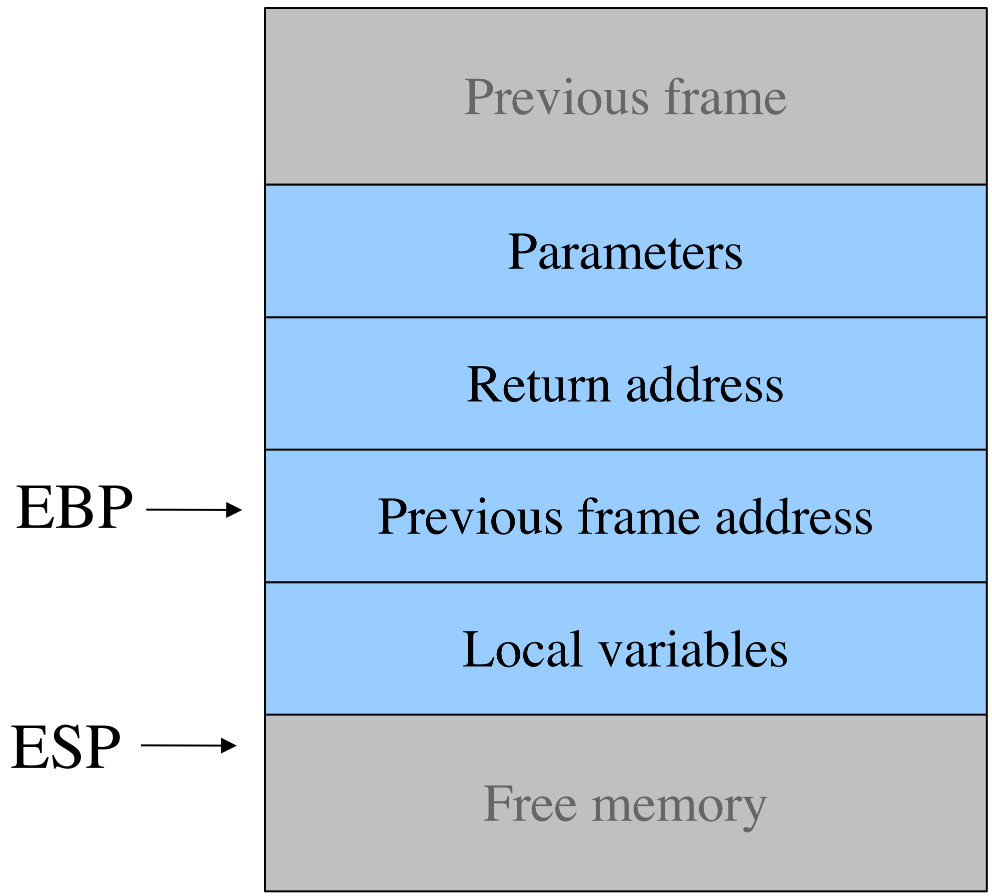
- In most architectures (Intel, Motorola, Sparc), stack grows towards bottom

- The ESP (stack pointer) register points to the top of the stack

- The EBP (base pointer) points to the current frame

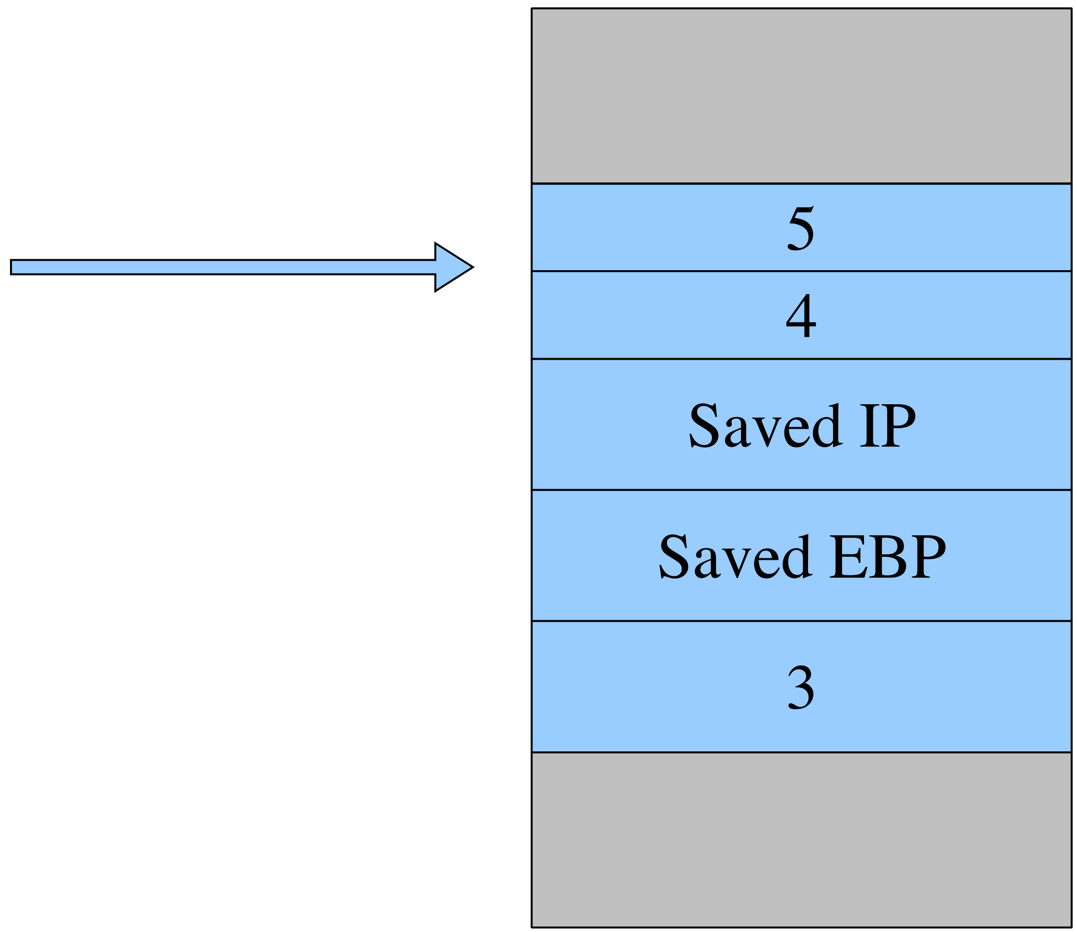
- Each frame contains:
  - Return address (where to jump at the end of the function)
  - Address of the previous frame
  - Parameters
  - Local variables of the function

Frame


Previous frame
Parameters
Return address
EBP
Previous frame address
Local variables
ESP
Free memory

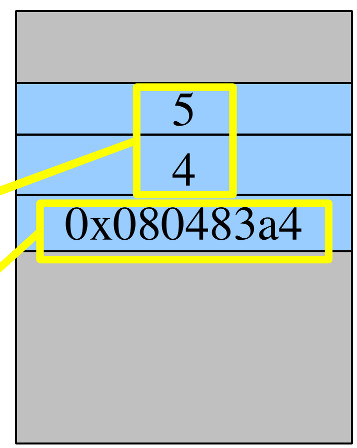
Procedure Call

```
int foo(int a, int b)
{
   int i = 3;

   return (a + b) * i;
}

int main()
{
   int e = 0;
   e = foo(4, 5);
   printf("%d", e);
}
```



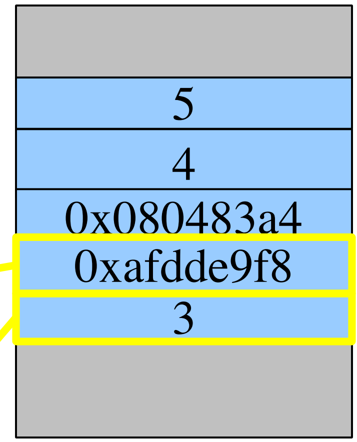
A closer look

```
(gdb) disas main
Dump of assembler code for function main:
0x0804836d <main+0>:     push   %ebp
0x0804836e <main+1>:     mov    %esp,%ebp
0x08048370 <main+3>:     sub    $0x18,%esp
0x08048373 <main+6>:     and    $0xfffffff0,%esp
0x08048376 <main+9>:     mov    $0x0,%eax
0x0804837b <main+14>:    add    $0xf,%eax
0x0804837e <main+17>:    add    $0xf,%eax
0x08048381 <main+20>:    shr    $0x4,%eax
0x08048384 <main+23>:    shl    $0x4,%eax
0x08048387 <main+26>:    sub    %eax,%esp
0x08048389 <main+28>:    movl   $0x0,0xfffffffc(%ebp)
0x08048390 <main+35>:    movl   $0x5,0x4(%esp)
0x08048398 <main+43>:    movl   $0x4,(%esp)
0x0804839f <main+50>:    call   0x8048354 <foo>
0x080483a4 <main+55>:    mov    %eax,0xfffffffc(%ebp)
```



A closer look

```
(gdb) breakpoint foo
Breakpoint 1 at 0x804835a
(gdb) run
Starting program: ./test1
Breakpoint 1, 0x0804835a in foo ()
(gdb) disas
Dump of assembler code for function foo:
0x08048354 <foo+0>:     push    %ebp
0x08048355 <foo+1>:     mov     %esp,%ebp
0x08048357 <foo+3>:     sub     $0x10,%esp
0x0804835a <foo+6>:     movl    $0x3,0xfffffffc(%ebp)
0x08048361 <foo+13>:    mov     0xc(%ebp),%eax
0x08048364 <foo+16>:    add     0x8(%ebp),%eax
0x08048367 <foo+19>:    imul    0xfffffffc(%ebp),%eax
0x0804836b <foo+23>:    leave
0x0804836c <foo+24>:    ret
End of assembler dump.
(gdb)
```



The “foo” frame

```
(gdb) stepi
0x08048361 in foo ()
(gdb) x/12wx $ebp-16
0xaf9d3cc8:  0xaf9d3cd8  0x080482de  0xa7faf360   0x00000003
0xaf9d3cd8:  0xafdde9f8  0x080483a4  0x00000004   0x00000005
0xaf9d3ce8:  0xaf9d3d08  0x080483df  0xa7fadff4   0x08048430
```