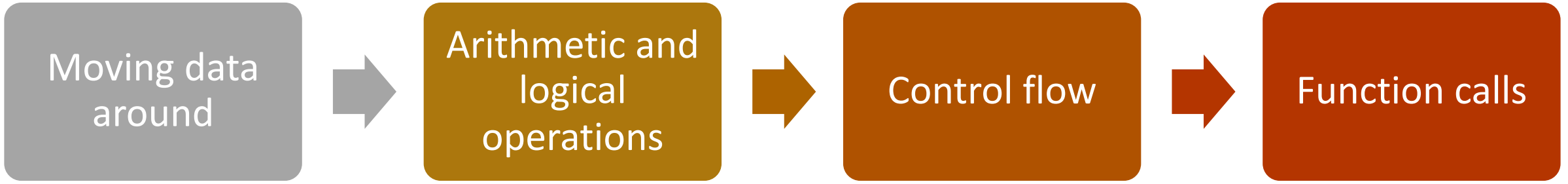
CS107, Lecture 19
Assembly: Control Flow and Function Calls

Reading: B&O 3.6

Learning Assembly



This Lecture

Reference Sheet: `cs107.stanford.edu/resources/x86-64-reference.pdf`
See more guides on Resources page of course website!

Learning Goals

- Understand how assembly implements loops and control flow
- Get practice using GDB to step through assembly and examine register contents.

Lecture Plan

- **Recap:** Control Flow Mechanics
- If statements
- Loops
  - While loops
  - For loops
- Other Instructions That Depend On Condition Codes

Lecture Plan

- **Recap: Control Flow Mechanics**
- If statements
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Control Flow Review

- %rip is a special register that stores the address of the next instruction to execute
- We can “interfere” with %rip to change the flow of our program’s execution
- **jmp** is one way to do this – it always jumps to the specified instruction location
- Conditional jumps are another way to do this – it jumps when its condition is true
- Conditional jumps work by relying on the *condition codes*; a set of 1-bit values that are updated by the result of the most recent arithmetic or logical operation.
- **cmp** is commonly paired with a conditional jump to check a condition
- **test** is another instruction that calculates bitwise & and updates condition codes

Exercise 1: Conditional jump

```
je target          jump if ZF is 1
```

Let %edi store 0x10. Will we jump in the following cases?

%edi `0x10`

1.
```
cmp $0x10,%edi
je  40056f
add  $0x1,%edi
```

2.
```
test $0x10,%edi
je   40056f
add  $0x1,%edi
```

Input your answer on PollEv:
pollev.com/cs107 or text CS107 to 22333 once to join.

Exercise 1: Conditional jump

```
je target
```

jump if ZF is 1

Let %edi store 0x10. Will we jump in the following cases?

%edi | 0x10

1.
```
cmp $0x10,%edi
je  40056f
add  $0x1,%edi
```

S2 - S1 == 0, so jump

2.
```
test $0x10,%edi
je   40056f
add  $0x1,%edi
```

S2 & S1 != 0, so don't jump

Lecture Plan

- **Recap:** Control Flow Mechanics
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Practice: Fill In The Blank

```
int if_then(int param1) {
  if ( __________ ) {
      __________;
  }

  return __________;
}
```

```
0000000000401126 <if_then>:
  401126:   cmp    $0x6,%edi
  401129:   je     40112f
  40112b:   lea    (%rdi,%rdi,1),%eax
  40112e:   retq
  40112f:   add    $0x1,%edi
  401132:   jmp    40112b
```

Practice: Fill In The Blank

```
int if_then(int param1) {
   if ( param1 == 6 ) {
         param1++;
   }

   return param1 * 2;
}
```

```
0000000000401126 <if_then>:
  401126:    cmp     $0x6,%edi
  401129:    je      40112f
  40112b:    lea     (%rdi,%rdi,1),%eax
  40112e:    retq
  40112f:    add     $0x1,%edi
  401132:    jmp     40112b
```

Common If-Else Construction

If-Else In C

```
long absdiff(long x, long y) {
    long result;
    if (x < y) {
        result = y - x;
    } else {
        result = x - y;
    }

    return result;
}
```

If-Else In Assembly pseudocode

```
Check opposite of code condition
Jump to else-body if test passes
If-body
Jump to past else-body
Else-body
Past else body
```

Practice: Fill in the Blank

If-Else In C

```
long absdiff(long x, long y) {
    long result;
    if ( x < y ) {
        result = y - x ;
    } else {
        result = x - y ;
    }

    return result;
}
```

```
401134 <+0>:   mov    %rsi,%rax
401137 <+3>:   cmp    %rsi,%rdi
40113a <+6>:   jge    0x401140 <absdiff+12>
40113c <+8>:   sub    %rdi,%rax
40113f <+11>:  retq
401140 <+12>:  sub    %rsi,%rdi
401143 <+15>:  mov    %rdi,%rax
401146 <+18>:  retq
```

If-Else In Assembly pseudocode

```
Check opposite of code condition
Jump to else-body if test passes
If-body
Jump to past else-body
Else-body
Past else body
```

If-Else Construction Variations

C Code

```
int test(int arg) {
    int ret;
    if (arg > 3) {
        ret = 10;
    } else {
        ret = 0;
    }

    ret++;
    return ret;
}
```

Assembly

```
401134 <+0>:   cmp    $0x3,%edi
401137 <+3>:   jle    0x401142 <test+14>
401139 <+5>:   mov    $0xa,%eax
40113e <+10>:  add    $0x1,%eax
401141 <+13>:  retq
401142 <+14>:  mov    $0x0,%eax
401147 <+19>:  jmp    0x40113e <test+10>
```

Lecture Plan

- **Recap:** Control Flow Mechanics
- If statements
- **Loops**
  - **While loops**
  - For loops
- Other Instructions That Depend On Condition Codes

GCC Common While Loop Construction

C

```
while (test) {
      body
}
```

Assembly

```
Check opposite of code condition
Skip loop if test passes
Body
Jump back to test
```

Loops and Control Flow

```
void loop() {
    int i = 0;
    while (i < 100) {
        i++;
    }
}
```

```
0x000000000040115c <+0>:    mov    $0x0,%eax
0x0000000000401161 <+5>:    cmp    $0x63,%eax
0x0000000000401164 <+8>:    jg     0x40116b <loop+15>
0x0000000000401166 <+10>:   add    $0x1,%eax
0x0000000000401169 <+13>:   jmp    0x401161 <loop+5>
0x000000000040116b <+15>:   retq
```

Check ***opposite of code condition***
Skip loop if test passes
Body
Jump back to test

Loops and Control Flow

```
void loop() {
    int i = 0;
    while (i < 100) {
        i++;
    }
}
```

```
0x000000000040115c <+0>:    mov    $0x0,%eax
0x0000000000401161 <+5>:    cmp    $0x63,%eax
0x0000000000401164 <+8>:    jg     0x40116b <loop+15>
0x0000000000401166 <+10>:   add    $0x1,%eax
0x0000000000401169 <+13>:   jmp    0x401161 <loop+5>
0x000000000040116b <+15>:   retq
```

Set %eax (i) to 0.

Check ***opposite of code condition***
Skip loop if test passes
Body
Jump back to test

Loops and Control Flow

```
void loop() {
    int i = 0;
    while (i < 100) {
        i++;
    }
}
```

```
0x000000000040115c <+0>:    mov    $0x0,%eax
0x0000000000401161 <+5>:    cmp    $0x63,%eax
0x0000000000401164 <+8>:    jg     0x40116b <loop+15>
0x0000000000401166 <+10>:   add    $0x1,%eax
0x0000000000401169 <+13>:   jmp    0x401161 <loop+5>
0x000000000040116b <+15>:   retq
```

Check opposite of code condition - jump if %eax is *greater than* 0x63. It does this by calculating %eax – 0x63 and then **jg** checks the resulting condition codes.

Check ***opposite of code condition***
Skip loop if test passes
Body
Jump back to test

Loops and Control Flow

```
void loop() {
    int i = 0;
    while (i < 100) {
        i++;
    }
}
```

```
0x000000000040115c <+0>:    mov    $0x0,%eax
0x0000000000401161 <+5>:    cmp    $0x63,%eax
0x0000000000401164 <+8>:    jg     0x40116b <loop+15>
0x0000000000401166 <+10>:   add    $0x1,%eax
0x0000000000401169 <+13>:   jmp    0x401161 <loop+5>
0x000000000040116b <+15>:   retq
```

Add 1 to %eax (i).

Check ***opposite of code condition***
Skip loop if test passes
Body
Jump back to test

Loops and Control Flow

```
void loop() {
    int i = 0;
    while (i < 100) {
        i++;
    }
}
```

```
0x000000000040115c <+0>:    mov    $0x0,%eax
0x0000000000401161 <+5>:    cmp    $0x63,%eax
0x0000000000401164 <+8>:    jg     0x40116b <loop+15>
0x0000000000401166 <+10>:   add    $0x1,%eax
0x0000000000401169 <+13>:   jmp    0x401161 <loop+5>
0x000000000040116b <+15>:   retq
```

Jump back to the loop test.

Check ***opposite of code condition***
Skip loop if test passes
Body
Jump back to test

Loops and Control Flow

```
void loop() {
    int i = 0;
    while (i < 100) {
        i++;
    }
}
```

```
0x000000000040115c <+0>:    mov    $0x0,%eax
0x0000000000401161 <+5>:    cmp    $0x63,%eax
0x0000000000401164 <+8>:    jg     0x40116b <loop+15>
0x0000000000401166 <+10>:   add    $0x1,%eax
0x0000000000401169 <+13>:   jmp    0x401161 <loop+5>
0x000000000040116b <+15>:   retq
```

When this test is true, we jump and skip the loop body.

Check ***opposite of code condition***
Skip loop if test passes
Body
Jump back to test

Loops and Control Flow

```
void loop() {
    int i = 0;
    while (i < 100) {
        i++;
    }
}
```

```
0x000000000040115c <+0>:    mov    $0x0,%eax
0x0000000000401161 <+5>:    cmp    $0x63,%eax
0x0000000000401164 <+8>:    jg     0x40116b <loop+15>
0x0000000000401166 <+10>:   add    $0x1,%eax
0x0000000000401169 <+13>:   jmp    0x401161 <loop+5>
0x000000000040116b <+15>:   retq
```

Then, we return from the function.

Check ***opposite of code condition***
Skip loop if test passes
Body
Jump back to test

GCC Other While Loop Construction

C

```
while (test) {
      body
}
```

Assembly

```
Jump to check
Body
Check code condition
Jump to body if test passes
```

```
0x0000000000400570 <+0>:     mov    $0x0,%eax
0x0000000000400575 <+5>:     jmp    0x40057a <loop+10>
0x0000000000400577 <+7>:     add    $0x1,%eax
0x000000000040057a <+10>:    cmp    $0x63,%eax
0x000000000040057d <+13>:    jle    0x400577 <loop+7>
0x000000000040057f <+15>:    repz retq
```

Lecture Plan

- **Recap:** Control Flow Mechanics
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Common For Loop Construction

C For loop

```
for (init; test; update) {
      body
}
```

C Equivalent While Loop

```
init
while(test) {
     body
     update
}
```

Assembly pseudocode

```
Init
Check opposite of code condition
Skip loop if test passes
Body
```

```
Update
Jump back to test
```

For loops and while loops are treated (essentially) the same when compiled down to assembly.

GCC For Loop Output

GCC Common For Loop Output

```
Initialization
Test
Jump past loop if success
Body
Update
Jump to test
```

Possible Alternative

```
Initialization
Jump to test
Body
Update
Test
Jump to body if success
```

Back to Our First Assembly

```
int sum_array(int arr[], int nelems) {
    int sum = 0;
    for (int i = 0; i < nelems; i++) {
        sum += arr[i];
    }
    return sum;
}
```

```
0000000000401136 <sum_array>:
  401136 <+0>:   mov    $0x0,%eax
  40113b <+5>:   mov    $0x0,%edx
  401140 <+10>:  cmp    %esi,%eax
  401142 <+12>:  jge    0x40114f <sum_array+25>
  401144 <+14>:  movslq %eax,%rcx
  401147 <+17>:  add    (%rdi,%rcx,4),%edx
  40114a <+20>:  add    $0x1,%eax
  40114d <+23>:  jmp    0x401140 <sum_array+10>
  40114f <+25>:  mov    %edx,%eax
  401151 <+27>:  retq
```

1. Which register is C code's `sum`?
2. Which register is C code's `i`?
3. Which assembly instruction is C code's `sum += arr[i]`?
4. What are the **`cmp`** and **`jge`** instructions doing?
   (**`jge`**: signed jump greater than/equal)

Demo: GDB and Assembly

`sum_array.c`

gdb tips

`layout split` (ctrl-x a: exit, ctrl-l: resize)	View C, assembly, and gdb (lab5)
`info reg`	Print all registers
`p $eax`	Print register value
`p $eflags`	Print all condition codes currently set
`b *0x400546`	Set breakpoint at assembly instruction
`b *0x400550 if $eax > 98`	Set **conditional breakpoint**
`ni`	Next assembly instruction
`si`	Step into assembly instruction (will step into function calls)

gdb tips

`p/x $rdi`	Print register value in hex
`p/t $rsi`	Print register value in binary
`x $rdi`	Examine the byte stored at this address
`x/4bx $rdi`	Examine 4 bytes starting at this address
`x/4wx $rdi`	Examine 4 ints starting at this address

Lecture Plan

- **Recap:** Control Flow Mechanics
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- **Other Instructions That Depend On Condition Codes**

Condition Code-Dependent Instructions

There are three common instruction types that use condition codes:

- **jmp** instructions conditionally jump to a different next instruction
- **set** instructions conditionally set a byte to 0 or 1
- new versions of **mov** instructions conditionally move data

`set`: Read condition codes

`set` instructions conditionally set a byte to 0 or 1.

- Reads current state of flags
- Destination is a single-byte register (e.g., %al) or single-byte memory location
- Does not perturb other bytes of register
- Typically followed by movzbl to zero those bytes

```
int small(int x) {
    return x < 16;
}
```

```
cmp $0xf,%edi
setle %al
movzbl %al, %eax
retq
```

`set`: Read condition codes

Instruction	Synonym	Set Condition (1 if true, 0 if false)
`sete D`	`setz`	Equal / zero
`setne D`	`setnz`	Not equal / not zero
`sets D`		Negative
`setns D`		Nonnegative
`setg D`	`setnle`	Greater (signed >)
`setge D`	`setnl`	Greater or equal (signed >=)
`setl D`	`setnge`	Less (signed <)
`setle D`	`setng`	Less or equal (signed <=)
`seta D`	`setnbe`	Above (unsigned >)
`setae D`	`setnb`	Above or equal (unsigned >=)
`setb D`	`setnae`	Below (unsigned <)
`setbe D`	`setna`	Below or equal (unsigned <=)

cmov: Conditional move

`cmovx src,dst` conditionally moves data in `src` to data in `dst`.

- Mov `src` to `dst` if condition `x` holds; no change otherwise
- `src` is memory address/register, `dst` is register
- May be more efficient than branch (i.e., jump)
- Often seen with C ternary operator: `result = test ? then: else;`

```
int max(int x, int y) {
    return x > y ? x : y;
}
```

```
cmp     %edi,%esi
mov     %edi, %eax
cmovge  %esi, %eax
retq
```

cmov: Conditional move

Instruction	Synonym	Move Condition
cmove S,R	cmovz	Equal / zero (ZF = 1)
cmovne S,R	cmovnz	Not equal / not zero (ZF = 0)
cmovs S,R		Negative (SF = 1)
cmovns S,R		Nonnegative (SF = 0)
cmovg S,R	cmovnle	Greater (signed >) (SF = 0 and SF = OF)
cmovge S,R	cmovnl	Greater or equal (signed >=) (SF = OF)
cmovl S,R	cmovnge	Less (signed <) (SF != OF)
cmovle S,R	cmovng	Less or equal (signed <=) (ZF = 1 or SF! = OF)
cmova S,R	cmovnbe	Above (unsigned >) (CF = 0 and ZF = 0)
cmovae S,R	cmovnb	Above or equal (unsigned >=) (CF = 0)
cmovb S,R	cmovnae	Below (unsigned <) (CF = 1)
cmovbe S,R	cmovna	Below or equal (unsigned <=) (CF = 1 or ZF = 1)

Last Lab: Conditional Move

```
int signed_division(int x) {
    return x / 4;
}
```

```
signed_division:
  leal 3(%rdi), %eax
  testl %edi, %edi
  cmovns %edi, %eax
  sarl $2, %eax
  ret
```

Put x + 3 into %eax

Check the sign of x

If x is nonnegative, put x into %eax

Divide %eax by 4

Recap

- **Recap:** Control Flow Mechanics
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- Other Instructions That Depend On Condition Codes

Lecture 19 takeaway: Loops and conditionals commonly use cmp or test along with jumps to conditionally skip over or repeat assembly instructions. We can use GDB to step through individual assembly instructions and view register contents.

Practice: Fill in the blanks

```
long loop(long a, long b) {
    long result = ___(1)___;
    while (___(2)___) {
      result = ____(3)_____;
      a = ___(4)___;
    }
    return result;
}
```

```
<+0>:   mov    $0x1,%eax
<+5>:   cmp    %rsi,%rdi
<+8>:   jge    0x1151 <loop+24>
<+10>:  lea    (%rdi,%rsi,1),%rdx
<+14>:  imul   %rdx,%rax
<+18>:  add    $0x1,%rdi
<+22>:  jmp    0x113e <loop+5>
<+24>:  retq
```

GCC common while loop construction:

Test

Jump past loop if fails

Body

Jump to test

https://godbolt.org/z/zrW6c5MGa

Practice: Fill in the blanks

```
long loop(long a, long b) {
    long result = ___(1)___;
    while (___(2)___) {
      result = ____(3)_____;
      a = ___(4)___;
    }
    return result;
}
```

```
<+0>:   mov    $0x1,%eax
<+5>:   cmp    %rsi,%rdi
<+8>:   jge    0x1151 <loop+24>
<+10>:  lea    (%rdi,%rsi,1),%rdx
<+14>:  imul   %rdx,%rax
<+18>:  add    $0x1,%rdi
<+22>:  jmp    0x113e <loop+5>
<+24>:  retq
```

GCC common while loop construction:

Test
Jump past loop if fails
Body
Jump to test

Practice: Fill in the blanks

```
long loop(long a, long b) {
    long result = _________;
    while (_________) {
      result = _____________;
      a = _________;
    }
    return result;
}
```

```
<+0>:   mov    $0x1,%eax

<+5>:   cmp    %rsi,%rdi
<+8>:   jge    0x1151 <loop+24>

<+10>:  lea    (%rdi,%rsi,1),%rdx
<+14>:  imul   %rdx,%rax
<+18>:  add    $0x1,%rdi

<+22>:  jmp    0x113e <loop+5>

<+24>:  retq
```

Practice: Fill in the blanks

```
long loop(long a, long b) {
    long result = ____1____;
    while (__a < b___) {
      result = result*(a+b);
      a = __a + 1___;
    }
    return result;
}
```

```
<+0>:   mov    $0x1,%eax

<+5>:   cmp    %rsi,%rdi
<+8>:   jge    0x1151 <loop+24>

<+10>:  lea    (%rdi,%rsi,1),%rdx
<+14>:  imul   %rdx,%rax
<+18>:  add    $0x1,%rdi

<+22>:  jmp    0x113e <loop+5>

<+24>:  retq
```

`test` practice: What's the C code?

```
0x400546 <test_func>     test   %edi,%edi
0x400548 <test_func+2>   jns    0x400550 <test_func+10>
0x40054a <test_func+4>   mov    $0xfeed,%eax
0x40054f <test_func+9>   retq
0x400550 <test_func+10>  mov    $0xaabbccdd,%eax
0x400555 <test_func+15>  retq
```

`test` practice: What's the C code?

```
0x400546 <test_func>     test   %edi,%edi
0x400548 <test_func+2>   jns    0x400550 <test_func+10>
0x40054a <test_func+4>   mov    $0xfeed,%eax
0x40054f <test_func+9>   retq
0x400550 <test_func+10>  mov    $0xaabbccdd,%eax
0x400555 <test_func+15>  retq
```

```
int test_func(int x) {
    if (x < 0) {
        return 0xfeed;
    }
    return 0xaabbccdd;
}
```

(or anything like this)

Practice: "Escape Room"

```
<escape_room+0>     lea   (%rdi,%rdi,1),%eax
<escape_room+3>     cmp   $0x5,%eax
<escape_room+6>     jg    0x114c <escape_room+19>
<escape_room+8>     cmp   $0x1,%edi
<escape_room+11>    je    0x1152 <escape_room+25>
<escape_room+13>    mov   $0x0,%eax
<escape_room+18>    retq
<escape_room+19>    mov   $0x1,%eax
<escape_room+24>    retq
<escape_room+25>    mov   $0x1,%eax
<escape_room+30>    retq
```

What must be passed to the escapeRoom function such that it returns true (1) and not false (0)?

You don't have to reverse-engineer C code exactly!

Just figure out the big picture!

Practice: "Escape Room"

```
<escape_room+0>     lea   (%rdi,%rdi,1),%eax
<escape_room+3>     cmp   $0x5,%eax
<escape_room+6>     jg    0x114c <escape_room+19>
<escape_room+8>     cmp   $0x1,%edi
<escape_room+11>    je    0x1152 <escape_room+25>
<escape_room+13>    mov   $0x0,%eax
<escape_room+18>    retq
<escape_room+19>    mov   $0x1,%eax
<escape_room+24>    retq
<escape_room+25>    mov   $0x1,%eax
<escape_room+30>    retq
```

What must be passed to the escapeRoom function such that it returns true (1) and not false (0)?

First param > 2 or == 1.

Exercise 2: Conditional jump

```
0000000004004d6 <if_then>:
  4004d6:   83 ff 06    cmp    $0x6,%edi
  4004d9:   75 03       jne    4004de <if_then+0x8>
  400rdb:   83 c7 01    add    $0x1,%edi
  4004de:   8d 04 3f    lea    (%rdi,%rdi,1),%eax
  4004e1:   c3          retq
```

%edi `0x5`

1. What is the value of `%rip` after executing the `jne` instruction?
   A. `4004d9`
   B. `4004db`
   C. `4004de`
   D. Other

2. What is the value of `%eax` when we hit the `retq` instruction?
   A. `4004e1`
   B. `0x2`
   C. `0xa`
   D. `0xc`
   E. Other

Exercise 2: Conditional jump

```
0000000004004d6 <if_then>:
  4004d6:   83 ff 06    cmp    $0x6,%edi
  4004d9:   75 03       jne    4004de <if_then+0x8>
  400rdb:   83 c7 01    add    $0x1,%edi
  4004de:   8d 04 3f    lea    (%rdi,%rdi,1),%eax
  4004e1:   c3          retq
```

%edi **0x5**

1. What is the value of `%rip` after executing the `jne` instruction?
   A. `4004d9`
   B. `4004db`
   C. `4004de`
   D. Other

2. What is the value of `%eax` when we hit the `retq` instruction?
   A. `4004e1`
   B. `0x2`
   C. `0xa`
   D. `0xc`
   E. Other