CSCI 2021: Introduction

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CSCI 2021 - Logistics

Reading

- Bryant/O'Hallaron: Ch 1
- C references: basic syntax, types, compilation

Goals

- Basic Model of Computation
- Begin discussion of C
- Course Mechanics

Podunk Model: CPU, Memory, Screen, Program

Most computers have 3 basic, physical components[1]

1. A CPU which can execute instructions
2. MEMORY where data is stored
3. Some sort of Input/Output device like a SCREEN

The CPU is executes a set of instructions that change MEMORY and the SCREEN, usually called a *program*

Example of a Running Computer Program

```
CPU: at instruction 10:             MEMORY:              SCREEN:
> 10: set #1024 to 1801             | Addr  | Value |
  11: set #1028 to 220              |-------+-------|
  12: sum #1024,#1028 into #1032    | #1024 |    19 |
  13: print #1024, "plus", #1028    | #1028 |    12 |
  14: print "is", #1032             | #1032 |  -137 |
```

[1]Of course it's a *little* more complex than this but the addage, "All models are wrong but some are useful." applies here. This class is about asking "what is really happening?" and going deep down the resulting rabbit hole.

Sample Run Part 1

```
CPU: at instruction 10:              MEMORY:            SCREEN:
> 10: set #1024 to 1801              | Addr  | Value |
  11: set #1028 to 220               |-------+-------|
  12: sum #1024,#1028 into #1032     | #1024 |    19 |
  13: print #1024, "plus", #1028     | #1028 |    12 |
  14: print "is", #1032              | #1032 |  -137 |

CPU: at instruction 11:              MEMORY:            SCREEN:
  10: set #1024 to 1801              | Addr  | Value |
> 11: set #1028 to 220               |-------+-------|
  12: sum #1024,#1028 into #1032     | #1024 |  1801 |
  13: print #1024, "plus", #1028     | #1028 |    12 |
  14: print "is", #1032              | #1032 |  -137 |

CPU: at instruction 12:              MEMORY:            SCREEN:
  10: set #1024 to 1801              | Addr  | Value |
  11: set #1028 to 220               |-------+-------|
> 12: sum #1024,#1028 into #1032     | #1024 |  1801 |
  13: print #1024, "plus", #1028     | #1028 |   220 |
  14: print "is", #1032              | #1032 |  -137 |
```

Sample Run Part 2

```
CPU: at instruction 13:                MEMORY:              SCREEN:
  10: set #1024 to 1801                | Addr  | Value |
  11: set #1028 to 220                 |-------+-------|
  12: sum #1024,#1028 into #1032       | #1024 |  1801 |
> 13: print #1024, "plus", #1028       | #1028 |   220 |
  14: print "is", #1032                | #1032 |  2021 |

CPU: at instruction 14:                MEMORY:              SCREEN:
  10: set #1024 to 1801                | Addr  | Value |    1801 plus 220
  11: set #1028 to 220                 |-------+-------|
  12: sum #1024,#1028 into #1032       | #1024 |  1801 |
  13: print #1024, "plus", #1028       | #1028 |   220 |
> 14: print "is", #1032                | #1032 |  2021 |

CPU: at instruction 15:                MEMORY:              SCREEN:
  10: set #1024 to 1801                | Addr  | Value |    1801 plus 220
  11: set #1028 to 220                 |-------+-------|    is 2021
  12: sum #1024,#1028 into #1032       | #1024 |  1801 |
  13: print #1024, "plus", #1028       | #1028 |   220 |
  14: print "is", #1032                | #1032 |  2021 |
> 15: ....
```

Observations: CPU and Program Instructions

- Program instructions are usually small, simple operations:
  - Put something in a specific memory cell using its **address**
  - Copy the contents of one cell to another
  - Do arithmetic (add, subtract, multiply, divide) with numbers in cells and specified constants like 5
  - Print stuff to the screen
- The CPU keeps track of which instruction to execute next
- In many cases after executing it moves ahead by one instruction but you all know **jumping** around is also possible
- This program is in **pseudocode**: not C or assembly or Java. . .
- Pseudocode can have almost anything in it so long as a human reader understands the meaning
- Real machines require more precise languages to execute as they are (still) much dumber than humans

Observations: Screen and Memory

Screen versus Memory

- Nothing is on the screen until it is explicitly `print`-ed by the program
- Normally you don't get to see memory while the program runs
- **Good programmers** can quickly form a mental picture of **what memory looks like** and draw it when needed
- You will draw memory diagrams in this class

Memory Cells

- Every cell has a fixed **ADDRESS** and its **CONTENTS** store a value
- Random Access Memory (RAM): the value in any memory cell can be retrieved FAST using its address
- My laptop has 16GB of memory = 134,217,728 integer boxes (!)
- Cell Address #'s never change: always cell #1024
- Cell Contents frequently change: `set #1024 to 19`

Variables: Named Memory Cells

- Dealing with raw memory addresses is tedious
- Any programming language worth its salt will have **variables**: symbolic names associated with cells
- **You pick variable names**; compiler/interpreter automatically translates to memory cell/address

```
PROGRAM ADDRESSES ONLY
CPU: at instruction 50:             MEMORY:
> 50: copy #1024 to #1032           | Addr  | Value |
  51: copy #1028 to #1024           |-------+-------|
  52: copy #1032 to #1028           | #1024 |    19 |
  53: print "first",#1024           | #1028 |    31 |
  54: print "second",#1028          | #1032 |     ? |

PROGRAM WITH NAMED CELLS            MEMORY:
CPU: at instruction 51:             | Addr  | Name | Value |
> 50: copy x to temp                |-------+------+-------|
  51: copy y to x                   | #1024 | x    |    19 |
  52: copy temp to y                | #1028 | y    |    31 |
  53: print "first",x               | #1032 | temp |     ? |
  54: print "second",y
```

Correspondence of C Programs to Memory

- C programs require cell names to be declared with the type of thing they will hold.
- The equal sign (=) means
  "store the result on the right in the cell named on the left"
- Creating a cell and giving it a value can be combined

```
int x;              // need a cell named x, holds an integer
x = 19;             // put 19 in cell x
int y = 31;         // need a cell named y and put 31 in it
int tmp = x + y;    // cell named tmp, fill with sum of x and y
```

Other Rules

- C/Java compilers read whole programs to figure out how many memory cells are needed based on declarations like `int a;` and `int c=20;`
- Lines that only declare a variable do nothing except indicate a cell is needed to the compiler
- In C, uninitialized variables may have arbitrary crud in them making them dangerous to use: *we'll find out why in this course*

Exercise: First C Snippet

- Demonstrate what the program snippet below does to memory and the screen
- Lines starting with // are comments, ignored
- `printf("%d %d\n",x,y)` prints the two variable values on the screen, more on this later

```
CPU: at line 50                 MEMORY:                      SCREEN:
> 50: int x;                    | Addr  | Name | Value |
  51: x = 19;                   |-------+------+-------|
  52: int y = 31;               | #1024 | x    | ?     |
  53: // swap x and y (?)       | #1028 | y    | ?     |
  54: x = y;                    | #1032 |      |       |
  55: y = x;
  56: printf("%d %d\n",x,y);
```

Answer: First C Snippet

```
CPU: at line 54                MEMORY:                    SCREEN:
  50: int x;                   | Addr  | Name | Value |
  51: x = 19;                  |-------+------+-------|
  52: int y = 31;              | #1024 | x    |    19 |
  53: // swap x and y (?)      | #1028 | y    |    31 |
> 54: x = y;                   | #1032 |      |       |
  55: y = x;
  56: printf("%d %d\n",x,y);
```

```
CPU: at line 55                MEMORY:                    SCREEN:
  50: int x;                   | Addr  | Name | Value |
  51: x = 19;                  |-------+------+-------|
  52: int y = 31;              | #1024 | x    |    31 |
  53: // swap x and y (?)      | #1028 | y    |    31 |
  54: x = y;                   | #1032 |      |       |
> 55: y = x;
  56: printf("%d %d\n",x,y);
```

```
CPU: at line 57                MEMORY:                    SCREEN:
  50: int x;                   | Addr  | Name | Value |   31 31
  51: x = 19;                  |-------+------+-------|
  52: int y = 31;              | #1024 | x    |    31 |
  53: // swap x and y (?)      | #1028 | y    |    31 |
  54: x = y;                   | #1032 |      |       |
  55: y = x;
  56: printf("%d %d\n",x,y);
> 57: ...
```

Clearly **incorrect**: how does one swap values properly?

First Full C Program: `swap_main.c`

```c
/* First C program which only has a main(). Demonstrates proper
   swapping of two int variables declared in main() using a third
   temporary variable. Uses printf() to print results to the screen
   (standard out). Compile run with:

   > gcc swap_main.c
   > ./a.out
*/

#include <stdio.h>                   // headers declare existence of functions
                                     // printf in this case
int main(int argc, char *argv[]){ // ENTRY POINT: always start in main()
  int x;                             // declare a variable to hold an integer
  x = 19;                            // set its value to 19
  int y = 31;                        // declare and set a variable
  int tmp = x;                       // declare and set to same value as x
  x = y;                             // put y's value in x's cell
  y = tmp;                           // put tmp's value in y's cell
  printf("%d %d\n",x,y);             // print the values of x and y
  return 0;                          // return from main(): 0 indicates success
}
```

- Correctly swaps two variables
- Executables always have a `main()` function: starting point
- Note inclusion of `stdio.h` **header** to declare `printf()` exists

Exercise: Functions in C, `swap_func.c`

```c
// C program which attempts to swap using a function.
//
// > gcc swap_func.c
// > ./a.out

#include <stdio.h>                  // declare existence printf()
void swap(int a, int b);            // function exists, defined below main

int main(int argc, char *argv[]){ // ENTRY POINT: start executing in main()
  int x = 19;
  int y = 31;
  swap(x, y);                       // invoke function to swap x/y (?)
  printf("%d %d\n",x,y);            // print the values of x and y
  return 0;
}

// Function to swap (?) contents of two memory cells
void swap(int a, int b){            // arguments to swap
  int tmp = a;                      // use a temporary to save a
  a = b;                            // a <- b
  b = tmp;                          // b <- tmp=a
  return;
}
```

Show the behavior of the `swap()` function shown, how it changes memory cells. *Does it "work"?*

Answers: The Function Call Stack: Calling swap()

```
    9: int main(...){           STACK: Caller main(), prior to swap()
   10:   int x = 19;            | FRAME    | ADDR  | SYM | VALUE |
   11:   int y = 31;            |----------+-------+-----+-------|
+-<12:   swap(x, y);            | main()   | #2048 | x   |    19 | stack frame
|  13:   printf("%d %d\n",x,y); | line:12  | #2044 | y   |    31 | for main()
|  14:   return 0;              |----------+-------+-----+-------|
V  15: }
|                               STACK: Callee swap() takes control
|  18: void swap(int a, int b){ | FRAME    | ADDR  | SYM | VALUE |
+->19:   int tmp = a;           |----------+-------+-----+-------|
   20:   a = b;                 | main()   | #2048 | x   |    19 | main() frame
   21:   b = tmp;               | line:12  | #2044 | y   |    31 | now inactive
   22:   return;                |----------+-------+-----+-------|
   23: }                        | swap()   | #2040 | a   |    19 | new frame
                                | line:19  | #2036 | b   |    31 | for swap()
                                |          | #2032 | tmp |     ? | now active
```

- Caller **pushes** a stack frame onto the **function call stack**
- Frame has space for all Callee parameters/locals
- Caller tracks where it left off to resume later
- Caller copies values to Callee frame for parameters
- Callee begins executing at its first instruction

Answers: Function Call Stack: Returning from swap()

```
    9: int main(...){
   10:   int x = 19;
   11:   int y = 31;
   12:   swap(x, y);
+->13:   printf("%d %d\n",x,y);
|  14:   return 0;
|  15: }
|
^  18: void swap(int a, int b){
|  19:   int tmp = a;
|  20:   a = b;
|  21:   b = tmp;
+-<22:   return;
   23: }
```

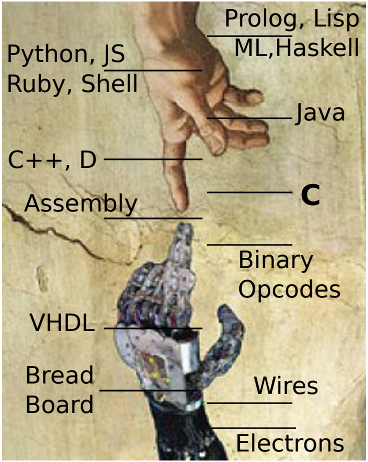
```
STACK: Callee swap() returning
| FRAME    | ADDR  | SYM | VALUE |
|----------+-------+-----+-------|
| main()   | #2048 | x   |    19 | inactive
| line:12  | #2044 | y   |    31 |
|----------+-------+-----+-------|
| swap()   | #2040 | a   |    31 | about to
| line:22  | #2036 | b   |    19 | return
|          | #2032 | tmp |    19 |

STACK: Caller main() gets cotrol back
| FRAME    | ADDR  | SYM | VALUE |
|----------+-------+-----+-------|
| main()   | #2048 | x   |    19 | now
| line:13  | #2044 | y   |    31 | active
|----------+-------+-----+-------|
```

- On finishing, Callee stack frame **pops** off, returns control back to Caller which resumes executing next instruction
- Callee may pass a return value to Caller but otherwise needs proper setup to alter the Caller stack frame.
- `swap()` does NOT swap the variables in `main()`

Motivation for C

Pure Abstraction



Bare Metal

Source

- If this were Java, Python, many others, discussion would be over.
- BUT: this is C which provides flexibility at a lower level
- Computer architecture has changed a LOT in the last 50 years but principles haven't
- C is approaching 50 years old and has changed little but still gets the job done

You just have to know C. Why? Because for all practical purposes, every computer in the world you'll ever use is a von Neumann machine, and C is a lightweight, expressive syntax for the von Neumann machine's capabilities.
–Steve Yegge, Tour de Babel

Von Neumann Machine

Some of the items below should start to feel familiar.

Processing

- Wires/gates that accomplish fundamental ops
- +, -, *, AND, OR, move, copy, shift, etc.
- Ops act on contents of memory cells to change them

Memory

- Giant array of bits/bytes so **everything** is represented as 1's and 0's, including instructions
- Memory cells accessible by address number

Control

- Memory address of next instruction to execute
- After executing, move ahead one unless instruction was to jump elsewhere

Input/Output

- Allows humans to interpret what is happening
- Often special memory locations for screen and keyboard

Swapping with Pointers/Addresses: swap_pointers.c

```
// C program which swaps values using a function with pointer arguments.

#include <stdio.h>                  // declare existence printf()
void swap_ptr(int *a, int *b);      // function exists, defined below main

int main(int argc, char *argv[]){ // ENTRY POINT: start executing in main()
  int x = 19;
  int y = 31;
  swap_ptr(&x, &y);                 // call swap() with addresses of x/y
  printf("%d %d\n",x,y);            // print the values of x and y
  return 0;
}

// Function to swap contents of two memory cells
void swap_ptr(int *a, int *b){      // a/b are addresses of memory cells
  int tmp = *a;                     // go to address a, copy value int tmp
  *a = *b;                          // copy val at addr in b to addr in a
  *b = tmp;                         // copy temp into address in b
  return;
}
```

- C allows direct use of memory cell addresses
- Operator & produces memory address of a variable
- `int *a`: pointer holds an address of integer(s)
- `*a`: operate on cell with address in a (dereference)

Swapping with Pointers/Addresses: Call Stack

```
    9: int main(...){               STACK: Caller main(), prior to swap()
   10:   int x = 19;                | FRAME    | ADDR  | NAME | VALUE |
   11:   int y = 31;                |----------+-------+------+-------|
+-<12:   swap_ptr(&x, &y);          | main()   | #2048 | x    |    19 |
|  13:   printf("%d %d\n",x,y);     | line:12  | #2044 | y    |    31 |
|  14:   return 0;                  |----------+-------+------+-------|
V  15: }
|                                   STACK: Callee swap() takes control
|  18: void swap_ptr(int *a,int *b){ | FRAME    | ADDR  | NAME | VALUE |
+->19:   int tmp = *a;              |----------+-------+------+-------|
   20:   *a = *b;                   | main()   | #2048 | x    |    19 |<-+
   21:   *b = tmp;                  | line:12  | #2044 | y    |    31 |<-|+
   22:   return;                    |----------+-------+------+-------|  ||
   23: }                            | swap_ptr| #2040 | a    | #2048 |--+|
                                    | line:19  | #2036 | b    | #2044 |---+
                                    |          | #2032 | tmp  |     ? |
```

- Syntax `&x` reads "Address of cell associated with `x`" or just "Address of `x`". Ampersand `&` is the address-of operator.
- Swap takes `int *a`: **pointer** to integer, is a memory address
- Values associated with `a`/`b` are the addresses of other cells

Swapping with Pointers/Addresses: Dereference/Use

```
 9: int main(...){                 LINE 19 executed: tmp gets 19
10:   int x = 19;                  | FRAME   | ADDR  | NAME | VALUE |
11:   int y = 31;                  |---------+-------+------+-------|
12:   swap_ptr(&x, &y);            | main()  | #2048 | x    |    19 |<-+
13:   printf("%d %d\n",x,y);       | line:12 | #2044 | y    |    31 |<-|+
14:   return 0;                    |---------+-------+------+-------|  ||
15: }                              | swap_ptr| #2040 | a    | #2048 |--+|
                                   | line:20 | #2036 | b    | #2044 |---+
18: void swap_ptr(int *a,int *b){  |         | #2032 | tmp  | ?->19 |
19:   int tmp = *a; // copy val at #2048 to #2032
>20:  *a = *b;
21:   *b = tmp;
22:   return;
23: }
```

- Syntax `*a` reads "Dereference a to operate on the cell pointed to by a" or just "Deref a"
- Line 19: cell #2040 contains address #2048, copy contents of #2048 into #2032 (`tmp`)

Aside: Star/Asterisk * has **3 uses** in C

1. Multiply as in

   ```
   w = c*d;
   ```

2. **Declare** a pointer as in

   ```
   int *x;  // pointer to integer(s)
   int b=4;
   x = &b;  // point x at b
   int **r; // pointer to int pointer(s)
   ```

3. **Dereference** a pointer as in

   ```
   int p = *x; // x must be an int pointer
               // retrieve contents at address
   ```

Three different context sensitive meanings for the same symbol makes * it hard on human to parse and was a BAD move by K&R.

```
int z = *x * *y + *(p+2); // ugly but normal in C
The duck is ready to eat. // English is more ambiguous
```

Swapping with Pointers/Addresses: Dereference/Assign

```
 9: int main(...){                 LINE 20 executed: alters x using a
10:   int x = 19;                  | FRAME    | ADDR  | NAME | VALUE |
11:   int y = 31;                  |----------+-------+------+-------|
12:   swap_ptr(&x, &y);            | main()   | #2048 | x    |19->31 |<-+
13:   printf("%d %d\n",x,y);       | line:12  | #2044 | y    |    31 |<-|+
14:   return 0;                    |----------+-------+------+-------|  ||
15: }                              | swap_ptr| #2040 | a    | #2048 |--+|
                                   | line:21  | #2036 | b    | #2044 |---+
18: void swap_ptr(int *a,int *b){  |          | #2032 | tmp  |    19 |
19:   int tmp = *a;
20:   *a = *b;      // copy val at #2044 (31) to #2048 (was 19)
>21:  *b = tmp;
22:   return;
23: }
```

- Dereference can be used to get values at an address
- Can be used on left-hand-side of assignment to set contents at an address
- Line 20: dereference a to change contents at #2048

Swapping with Pointers/Addresses: Deref 2

```
 9: int main(...){                LINE 21 executed: alters y using b
10:   int x = 19;                 | FRAME    | ADDR  | NAME | VALUE |
11:   int y = 31;                 |----------+-------+------+-------|
12:   swap_ptr(&x, &y);           | main()   | #2048 | x    |    31 |<-+
13:   printf("%d %d\n",x,y);      | line:12  | #2044 | y    |31->19 |<-|+
14:   return 0;                   |----------+-------+------+-------|  ||
15: }                             | swap_ptr| #2040 | a    | #2048 |--+|
                                  | line:22  | #2036 | b    | #2044 |---+
18: void swap_ptr(int *a,int *b){ |          | #2032 | tmp  |    19 |
19:   int tmp = *a;
20:   *a = *b;
21:   *b = tmp;     // copy val at #2032 (19) to #2044 (was 31)
>22:   return;
23: }
```

- Can be used on left-hand-side of assignment to set contents at an address
- Line 21: dereference `*b = ...` to change contents at #2044
- Use of variable name `tmp` retrieves contents of cell associated with `tmp`

Swapping with Pointers/Addresses: Returning

```
    9: int main(...){
   10:   int x = 19;
   11:   int y = 31;
   12:   swap_ptr(&x, &y);
+->13:   printf("%d %d\n",x,y);
|  14:   return 0;
|  15: }
|
|  18: void swap_ptr(int *a,int *b){
|  19:   int tmp = *a;
|  20:   *a = *b;
|  21:   *b = tmp;
+-<22:   return;
   23: }
```

```
LINE 22: prior to return
| FRAME    | ADDR  | NAME | VALUE |
|---------+-------+------+-------|
| main()   | #2048 | x    |    31 |<-+
| line:12  | #2044 | y    |    19 |<-|+
|---------+-------+------+-------|  ||
| swap_ptr| #2040 | a    | #2048 |--+|
| line:22  | #2036 | b    | #2044 |---+
|          | #2032 | tmp  |    19 |

LINE 12 finished/return pops frame
| FRAME    | ADDR  | NAME | VALUE |
|---------+-------+------+-------|
| main()   | #2048 | x    |    31 |
| line:13  | #2044 | y    |    19 |
|---------+-------+------+-------|
```

- `swap()` finished so frame pops off
- Variables `x,y` in `main()` have changed due to use of references to them.

Important Principle: Non-local Changes

- Pointers allow one function to change the stack variables associated with other running functions
- Common beginner example: `scanf()` family which is used to read values from terminal or files
- Snippet from `scanf_demo.c`

```
1 int main(...){
2   int num = -1;
3   scanf("%d", &num);  // address
4   printf("%d\n",num); // value
4   return 0;
5 }
```

- See `scanf_error.c` : forgetting & yields great badness

```
scanf() called
| FRAME     | ADDR  | NAME | VALUE |
|-----------+-------+------+-------|
| main():3  | #2500 | num  | -1    |<-+
|-----------+-------+------+-------|  |
| scanf()   | #2496 | fmt  | #400  |  |
|           | #2036 | arg1 | #2500 |--+

scanf() changes contents of #2500
| FRAME     | ADDR  | NAME | VALUE |
|-----------+-------+------+-------|
| main():3  | #2500 | num  | 5     |<-+
|-----------+-------+------+-------|  |
| scanf()   | #2496 | fmt  | #400  |  |
|           | #2036 | arg1 | #2500 |--+

scanf() returns
| FRAME     | ADDR  | NAME | VALUE |
|-----------+-------+------+-------|
| main():4  | #2500 | num  | 5     |
|-----------+-------+------+-------|
```

Uncle Ben Said it Best…

All of these apply to our context..

- **Pointers allow any part of a C program to modify any piece of program data.**
- A BLESSING: fine control of memory, closer to the machine, opens up efficiency
- A CURSE: opens up many **errors** not possible in langs like Java/Python which restrict use of memory

1972 - Dennis Ritchie invents a powerful gun that shoots both forward and backward simultaneously. Not satisfied with the number of deaths and permanent maimings from that invention he invents C and Unix.
– A Brief, Incomplete, and Mostly Wrong History of Pro-

Beneath the C

Assembly

- More readable than binary
- Directly translated to binary using assemblers
- Specific to each CPU, close to the machine

Binary Opcodes

- 1's and 0's, represent the digital signal of the machine
- Codes corresponds to instructions directly understood by processor

```
ASSEMBLY                     HEXADECIMAL/BINARY OPCODES
push   %ebp                   0: 55 = 0101 0101
mov    %esp,%ebp              1: 89 e5
and    $0xfffffff0,%esp       3: 83 e4 f0
sub    $0x10,%esp             6: 83 ec 10
movl   $0x0,(%esp)            9: c7 04 24 00 00 00 00
call   11 <main+0x11>        10: e8 fc ff ff ff
leave                        15: c9 = 1100 1001
ret                          16: c3 = 1100 0011
```

Looks like **fun**, right? You better hope so: assembly is 1 month away...

CSCI 2021: Course Goals

- Basic proficiency at C programming
- Knowledge of running programs in physical memory including the stack, heap, global, and text areas of memory
- Understanding of the essential elements of assembly languages
- Knowledge of the correspondence between high-level program constructs.
- Ability to use a symbolic debugger
- Basic understanding of how data is encoded in binary
- Knowledge of computer memory systems
- Basic knowledge of computer architecture