CSCB09 Software Tools and Systems Programming
Memory Model / IO

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Department of Computer and Mathematical Sciences - UTSC

Today's lecture

Memory Model (cont.)

- Memory Issues
- Memory Model worksheet

IO

- Quick recap
- IO Worksheet

Memory Model (cont.)

The *Complete* Memory Model

Static data

Space for the *evil* **global** variables and variables declared as **static**

Dynamic data (Heap)

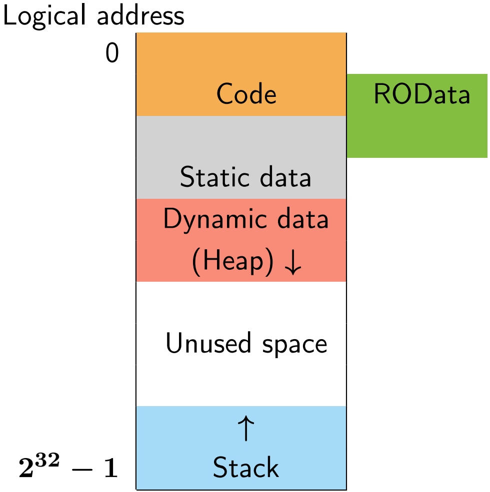
Space for dynamically allocated data structures (`malloc`, `calloc`).

Stack

Space for variables created in function calls: a function's parameters and a function's local variables

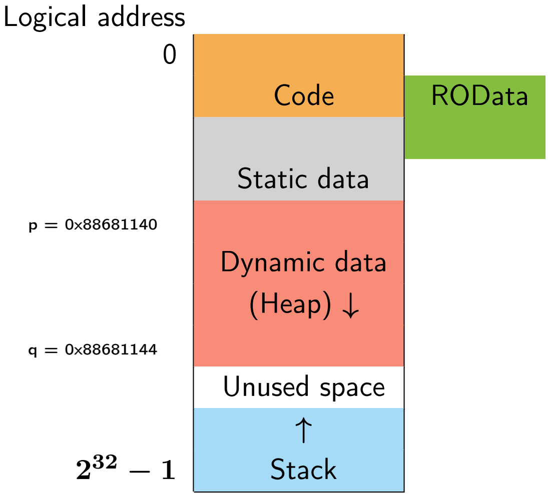
Code/Text

string literals: ROData (read-only data) code/text, or static data depending on platform



- Suppose that,

```
p = malloc(...);
q = malloc(...);
```

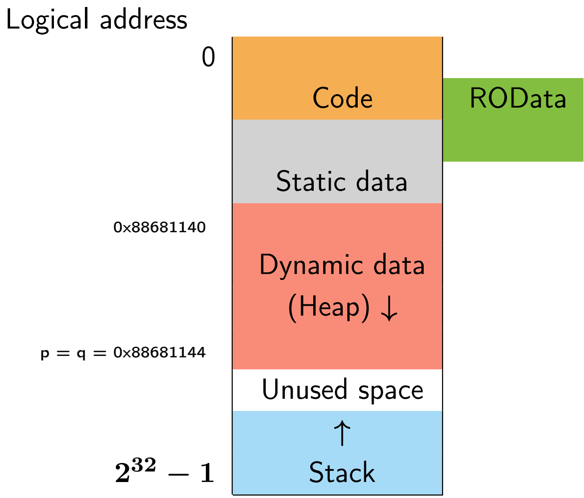


- Suppose that,

```
p = malloc(...);
q = malloc(...);
```

- Next consider,

```
p = q;
```



Memory Leaks

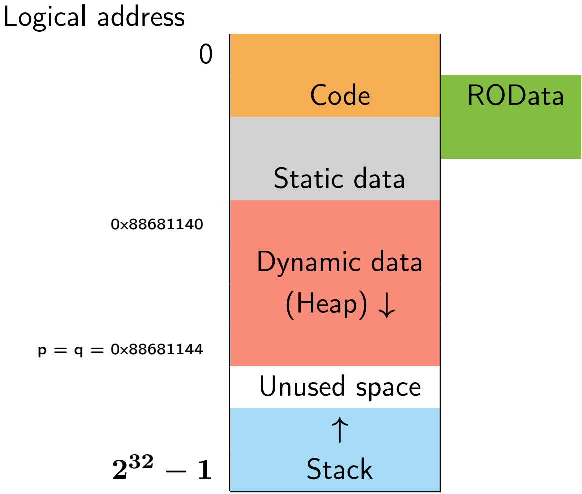
- Suppose that,

```
p = malloc(...);
q = malloc(...);
```

- Next consider,

```
p = q;
```

- What happens?



Memory Leaks

- Suppose that,

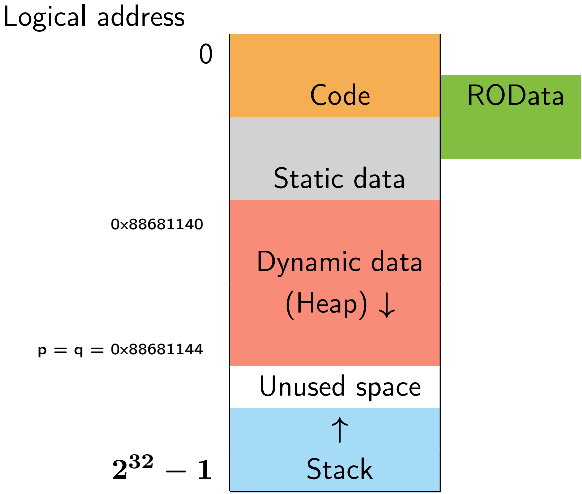
  `p = malloc(...);`

  `q = malloc(...);`

- Next consider,

  `p = q;`

- **Problem**: we have no way of accessing `p`'s old block.
- We also have no way of freeing `p`'s old block.



Memory Leaks

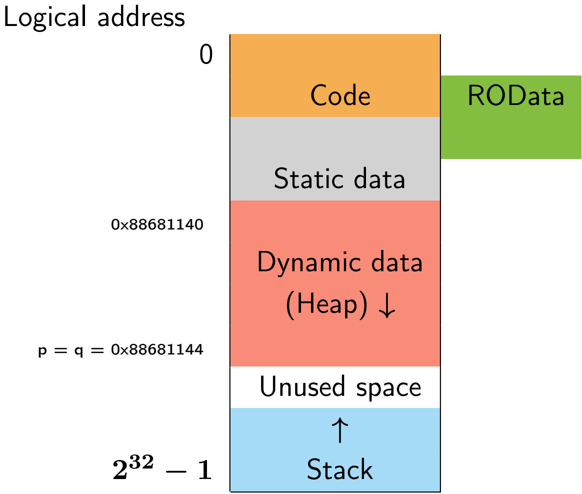
- Suppose that,

```
p = malloc(...);
q = malloc(...);
```

- Next consider,

```
p = q;
```

- **Problem**: we have no way of accessing `p`'s old block.
- We also have no way of freeing `p`'s old block.
- This is called a **memory leak**. One of the most common programming errors.



Dangling Pointers

```c
char *p = malloc(5);
...
free(p);
```

p is now a pointer to memory it does not own.

```c
strcpy(p,"abcd");    // Bad things can
    happen
```

Memory Model worksheet

Code Fragment	Space?	Where?	De-allocated when?

<pre>int main() {
  int i;
}</pre>			

<pre>int fun() {
  float i;
}
 	
int main() {
  fun();
}</pre>			

<pre>int fun(char i)
     {
 	
  . . .
}
 	
int main() {
  fun('a');
}</pre>			

Memory Model worksheet

Code Fragment	Space?	Where?	De-allocated when?

`int main() {`
`  int i;`
`}`
	`sizeof(int)`		

`int fun() {`
`  float i;`
`}`
 	
`int main() {`
`  fun();`
`}`			

`int fun(char i)`
`    {`
 	
`  . . .`
`}`
 	
`int main() {`
`  fun('a');`
`}`			

Code Fragment	Space?	Where?	De-allocated when?

`int main() {`
`  int i;`
`}`
	`sizeof(int)`	Stack	

`int fun() {`
`  float i;`
`}`
 	
`int main() {`
`  fun();`
`}`			

`int fun(char i)`
`    {`
 	
`  . . .`
`}`
 	
`int main() {`
`  fun('a');`
`}`			

Memory Model worksheet

<table>
<tr><th>Code Fragment</th><th>Space?</th><th>Where?</th><th>De-allocated when?</th></tr>
<tr><td><pre>int main() {
  int i;
}</pre></td><td><code>sizeof(int)</code></td><td>Stack</td><td>when program ends</td></tr>
<tr><td><pre>int fun() {
  float i;
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int main() {
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  int i;
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  float i;
}

int main() {
  fun();
}</pre></td><td><code>sizeof(float)</code></td><td></td><td></td></tr>
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  . . .
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int main() {
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  int i;
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<tr><td><pre>int fun() {
  float i;
}

int main() {
  fun();
}</pre></td><td><code>sizeof(float)</code></td><td>Stack</td><td></td></tr>
<tr><td><pre>int fun(char i)
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  . . .
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int main() {
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Memory Model worksheet

Code Fragment	Space?	Where?	De-allocated when?

`int main() {`
`  int i;`
`}`
	`sizeof(int)`	Stack	when program ends

`int fun() {`
`  float i;`
`}`
 	
`int main() {`
`  fun();`
`}`
	`sizeof(float)`	Stack	when `fun` returns

`int fun(char i)`
`    {`
 	
`  . . .`
`}`
 	
`int main() {`
`  fun('a');`
`}`			

Memory Model worksheet

Code Fragment	Space?	Where?	De-allocated when?

`int main() {`
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`  float i;`
`}`
 	
`int main() {`
`  fun();`
`}`
	`sizeof(float)`	Stack	when `fun` returns

`int fun(char i)`
`    {`
 	
`  . . .`
`}`
 	
`int main() {`
`  fun('a');`
`}`
	`1 == sizeof(char)`		

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<tr><td><pre>int fun(char i)
    {

  . . .
}

int main() {
  fun('a');
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Code Fragment	Space?	Where?	De-allocated when?

`int main() {`
`  int i;`
`}`
	`sizeof(int)`	Stack	when program ends

`int fun() {`
`  float i;`
`}`
 	
`int main() {`
`  fun();`
`}`
	`sizeof(float)`	Stack	when `fun` returns

`int fun(char i)`
`    {`
 	
`  . . .`
`}`
 	
`int main() {`
`  fun('a');`
`}`
	`1 == sizeof(char)`	Stack	when `fun` returns

Memory Model worksheet (cont.)

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<tr><th>Code Fragment</th><th>Space?</th><th>Where?</th><th>De-allocated when?</th></tr>
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   char i[10] =
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         hello";

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Memory Model worksheet (cont.)

Code Fragment	Space?	Where?	De-allocated when?

`int main() {`
`  char i[10] = "hello";`
`}`			

`int main() {`
`  char *i;`
`}`
	`sizeof(char *)`		

`int main() {`
`  int *i;`
`}`			

`int main() {`
`  char *i = "hello";`
`}`			

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`int main() {`
`  char i[10] =`
`      "hello";`
 	
`}`			

`int main() {`
`  char *i;`
 	
`}`
	`sizeof(char *)`	Stack	when program ends

`int main() {`
`  int *i;`
 	
`}`
	`sizeof(int *)`		

`int main() {`
`  char *i = "`
`      hello";`
 	
`}`			

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  char i[10] =
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  char *i;
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Memory Model worksheet (cont.)

Code Fragment	Space?	Where?	De-allocated when?

`int main() {`
`  char i[10] =`
`      "hello";`
 	
`}`
	`10*sizeof(char) ==`
	
	`10`
		Stack	

`int main() {`
`  char *i;`
 	
`}`
	`sizeof(char *)`	Stack	when program ends

`int main() {`
`  int *i;`
 	
`}`
	`sizeof(int *)`	Stack	when program ends

`int main() {`
`  char *i = "`
`      hello";`
 	
`}`			

Memory Model worksheet (cont.)

Code Fragment	Space?	Where?	De-allocated when?

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`      "hello";`
`}`
	`10*sizeof(char) ==`
	`10`
		Stack	when program ends

`int main() {`
`  char *i;`
`}`
	`sizeof(char *)`	Stack	when program ends

`int main() {`
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}</pre></td><td><code>sizeof(char *)</code></td><td>Stack</td><td>when program ends</td></tr>
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}</pre></td><td><code>sizeof(int *)</code></td><td>Stack</td><td>when program ends</td></tr>
<tr><td><pre>int main() {
  char *i = "
      hello";
}</pre></td><td><code>sizeof(char *) ; 6 == 6*sizeof(char)</code></td><td></td><td></td></tr>
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Memory Model worksheet (cont.)

Code Fragment	Space?	Where?	De-allocated when?
`int main() { char i[10] = "hello"; }`	`10*sizeof(char) == 10`	Stack	when program ends
`int main() { char *i; }`	`sizeof(char *)`	Stack	when program ends
`int main() { int *i; }`	`sizeof(int *)`	Stack	when program ends
`int main() { char *i = "hello"; }`	`sizeof(char *) ; 6 == 6*sizeof(char)`	Stack; read-only memory	

Memory Model worksheet (cont.)

Code Fragment	Space?	Where?	De-allocated when?

`int main() {`
`  char i[10] =`
`      "hello";`
`}`
	`10*sizeof(char) == 10`	Stack	when program ends

`int main() {`
`  char *i;`
`}`
	`sizeof(char *)`	Stack	when program ends

`int main() {`
`  int *i;`
`}`
	`sizeof(int *)`	Stack	when program ends

`int main() {`
`  char *i = "`
`      hello";`
`}`
	`sizeof(char *) ; 6 == 6*sizeof(char)`	Stack; read-only memory	when program ends; when program ends

Memory Model worksheet (cont.)

Code Fragment	Space?	Where?	De-allocated when?

<pre>int fun(int *i) {
  . . .
}
 	
int main() {
  int i[5] =
      {4,5,2,5,1};
 	
  fun(i);
}</pre>			

<pre>int main() {
  int *i;
  i = malloc(
      sizeof(
      int));
  ...
}</pre>			

Memory Model worksheet (cont.)

Code Fragment	Space?	Where?	De-allocated when?

`int fun(int *i) {`
`  . . .`
`}`
 	
`int main() {`
`  int i[5] =`
`      {4,5,2,5,1};`
 	
`  fun(i);`
`}`
	`sizeof(int *)`
	
	`5*sizeof(int)`		

`int main() {`
`  int *i;`
`  i = malloc(`
`      sizeof(`
`      int));`
`  ...`
`}`			

Memory Model worksheet (cont.)

Code Fragment	Space?	Where?	De-allocated when?

`int fun(int *i) {`
`  . . .`
`}`
	`sizeof(int *)`	Stack	

`int main() {`
`  int i[5] = {4,5,2,5,1};`
`  fun(i);`
`}`
	`5*sizeof(int)`	Stack	

`int main() {`
`  int *i;`
`  i = malloc(sizeof(int));`
`  ...`
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Code Fragment	Space?	Where?	De-allocated when?
`int fun(int *i) { . . . }`	`sizeof(int *)`	Stack	when fun returns
`int main() { int i[5] = {4,5,2,5,1}; fun(i); }`	`5*sizeof(int)`	Stack	when program ends
`int main() { int *i; i = malloc( sizeof( int)); ... }`	`sizeof(int *)` / `sizeof(int)`		

Memory Model worksheet (cont.)

Code Fragment	Space?	Where?	De-allocated when?
`int fun(int *i) { . . . }`	`sizeof(int *)`	Stack	when fun returns
`int main() { int i[5] = {4,5,2,5,1}; fun(i); }`	`5*sizeof(int)`	Stack	when program ends
`int main() { int *i; i = malloc( sizeof( int)); ... }`	`sizeof(int *)` / `sizeof(int)`	Stack / Heap	

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<tr><td><pre>int main() {
  int *i;
  i = malloc(
      sizeof(
      int));
  ...
}</pre></td><td><code>sizeof(int *)</code> / <code>sizeof(int)</code></td><td>Stack / Heap</td><td>when program ends / when free called or when program ends</td></tr>
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```c
void fun(int **
    i) {
  *i = malloc(
      sizeof(
      int) * 7)
      ;
  ...
}
```

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<tr><td>

```c
int main() {
  int *i;
  fun(&i);
  free(i);
}
```

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7*sizeof(int)</td><td></td><td></td></tr>
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Worksheet Q2

Write a program that declares 3 strings:

- The first named first should be set to the value "Monday", and be stored on the *stack frame* for main.
- second should be a *string literal* with the value "Tuesday".
- third should have value "Wednesday" and be on the *heap*.
- The pointers for second and third will be in *stack frame* for main.

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- The pointers for second and third will be in *stack frame* for main.

```c
#include <stdlib.h>
#include <string.h>

int main() {
  // store in stack
  char first[] = "Monday";
  // string literal
  char *second = "Tuesday";
  // in heap
  char *third = malloc(sizeof(char) * 10);
  strncpy(third, "Wednesday", 10);

  return 0;
}
```

Worksheet Q3

- Write statements to shorten the strings to the abbreviations for the day names.
  For example, change "Monday" to "Mon".
  Which string can not be changed in place? Why not?

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```
first[3] = '\0';
// second[3] = '\0'; // This will cause undefined behaviour
third[3] = '\0';
```

Worksheet Q5

- Add to your program so that it declares an array string list of 3 pointers to char and point the elements to first, second, and third, respectively.
- So now you have an array of strings. Where is the memory allocated for this array?

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```
char *array[3];

array[0] = first;
array[1] = second;
array[2] = third;
```

IO

Storing Characters

- Characters are 1 byte long integers
- The ASCII code maps characters to corresponding int.
- E.g. `char c = 'A'` is identical to `char c = 65`
- When you store an 'A' the 8 bits that are stored are: 01000001 (representing the number 65 in binary).

Character Name	Char	Code	Decimal	Binary	Hex
Null	NUL	Ctrl @	0	00000000	00
Start of Heading	SOH	Ctrl A	1	00000001	01
Start of Text	STX	Ctrl B	2	00000010	02
End of Text	ETX	Ctrl C	3	00000011	03
End of Transmit	EOT	Ctrl D	4	00000100	04
Enquiry	ENQ	Ctrl E	5	00000101	05
Acknowledge	ACK	Ctrl F	6	00000110	06
Bell	BEL	Ctrl G	7	00000111	07
Back Space	BS	Ctrl H	8	00001000	08
Horizontal Tab	TAB	Ctrl I	9	00001001	09
Line Feed	LF	Ctrl J	10	00001010	0A
Vertical Tab	VT	Ctrl K	11	00001011	0B
Form Feed	FF	Ctrl L	12	00001100	0C
Carriage Return	CR	Ctrl M	13	00001101	0D
Shift Out	SO	Ctrl N	14	00001110	0E
Shift In	SI	Ctrl O	15	00001111	0F
Data Line Escape	DLE	Ctrl P	16	00010000	10
Device Control 1	DC1	Ctrl Q	17	00010001	11
Device Control 2	DC2	Ctrl R	18	00010010	12
Device Control 3	DC3	Ctrl S	19	00010011	13
Device Control 4	DC4	Ctrl T	20	00010100	14
Negative Acknowledge	NAK	Ctrl U	21	00010101	15
Synchronous Idle	SYN	Ctrl V	22	00010110	16
End of Transmit Block	ETB	Ctrl W	23	00010111	17
Cancel	CAN	Ctrl X	24	00011000	18

SRC: `https://www.eso.org/~ndelmott/ascii.html`

Capital A	A	Shift A	65	01000001	41
Capital B	B	Shift B	66	01000010	42
Capital C	C	Shift C	67	01000011	43
Capital D	D	Shift D	68	01000100	44
Capital E	E	Shift E	69	01000101	45
Capital F	F	Shift F	70	01000110	46
Capital G	G	Shift G	71	01000111	47
Capital H	H	Shift H	72	01001000	48
Capital I	I	Shift I	73	01001001	49
Capital J	J	Shift J	74	01001010	4A
Capital K	K	Shift K	75	01001011	4B
Capital L	L	Shift L	76	01001100	4C
Capital M	M	Shift M	77	01001101	4D
Capital N	N	Shift N	78	01001110	4E
Capital O	O	Shift O	79	01001111	4F
Capital P	P	Shift P	80	01010000	50
Capital Q	Q	Shift Q	81	01010001	51
Capital R	R	Shift R	82	01010010	52
Capital S	S	Shift S	83	01010011	53
Capital T	T	Shift T	84	01010100	54
Capital U	U	Shift U	85	01010101	55
Capital V	V	Shift V	86	01010110	56
Capital W	W	Shift W	87	01010111	57
Capital X	X	Shift X	88	01011000	58
Capital Y	Y	Shift Y	89	01011001	59
Capital Z	Z	Shift Z	90	01011010	5A
Left Bracket	[	[	91	01011011	5B
Backward Slash	\	\	92	01011100	5C
Right Bracket	]	]	93	01011101	5D

Binary I/O

- `fgets` reads characters, `fprintf` writes characters.
- By contrast, `fread` and `fwrite` operate on bytes.

```
size_t  fread(void *ptr, size_t size,
              size_t nmemb, FILE *
                 stream);
```

read `nmemb` × `size` bytes into memory at `ptr`

returns number of items read

```
size_t fwrite(const void *ptr, size_t
    size,
```

write `nmemb` × `size` bytes from `ptr` to the file pointer stream

returns number of items written

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returns number of items read

```
/* write an integer to the file */
int num = 1999999;
n = fwrite(&num, sizeof(num), 1, fp);
```

```
size_t fwrite(const void *ptr, size_t
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```

write `nmemb` × `size` bytes from `ptr` to the file pointer stream

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```
/* read an integer from the file */
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What's written to the file? (show the bits)	**Code**	**What's in the Memory?** (show the bits)
	`char ch = 'A';`	
	`fprintf(fp, "A");`	
	`char ch = 'A';` `fprintf(fp, "%c", ch);`	
	`fprintf(fp, "5");`	
	`char ch = '5';` `fprintf(fp,"%c",ch);`	
	`int i = 5;`	

(Assuming size of an integer is 4 bytes)

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What's written to the file? (show the bits)	**Code**	**What's in the Memory?** (show the bits)
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Observe that text representation of 5 takes one byte, binary representation of integer takes 4 bytes.

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Binary versus text representation of integers

- Binary representation of integers is 4 bytes (assuming 32-bit architecture)
- Number of characters in text representation is equal to number of decimal digits. E.g. integer 999 takes 3 characters.

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What range of integers uses more bytes to store in binary than text?

$\underbrace{ddd...ddd}_{\text{n } digits} \rightsquigarrow n$ bytes in text/char $\Rightarrow n > 4$

You should have noticed that more bytes are written for the `int i` than just a single character. Identify (with justification) the range of integers `i` such that:

1. more bytes are required to store `i` in binary –using `fwrite(&i, sizeof(int), 1, fp)`– than in text –using `fprintf(fp, "%d", i)`–.
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   $>=$ 10000