Byte-oriented memory, pointers, and IO

Troels Henriksen

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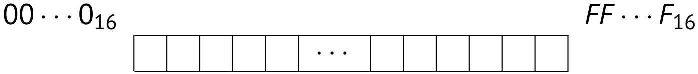
Based on slides by Randal E. Bryant and David R. O'Hallaron

A machine view of memory

A machine view of text

Binary IO

Byte-oriented memory organisation



- **Programs refer to data by address**
  - Conceptually, envision as large array of bytes.
    - It’s not really, but it works as a model.
  - An address is like an index into that array.
    - A *pointer* stores an address.
    - **Addresses are ultimately just unsigned integers.**
- **System provides private address space to each “process”**

Machine words

Any given computer has a “word size”

- “Native” size of integer-valued data.
  - But especially of addresses.
- 32-bit machines used to be the norm and are still found.
  - 2^{32} different addresses, meaning $4GiB$ can be addressed.
- 64-bit machines are most common.
  - 2^{64} different addresses, meaning $18EiB$ can be addressed.
  - $18.4 \cdot 10^{18}$ bytes.
  - Current machines only use lower 48 bits of address.
- Machines also support other data formats.
  - Fractions or multiples of word size.
  - Always integral number of types.
  - Smaller types (e.g. 16-bit integers) take less space in memory, but are (usually) not faster than the “native” words.
  - But bigger types (e.g. 128-bit integers) are slower.

Word-oriented memory organisation

- **Addresses specify byte locations**
  - Address of first byte in word.
  - Addresses of successive words differ by 4 (32 bit) or 8 (64 bit).
  - *Addresses always refer to a byte* even when addressing larger types.
- **We can take the address of any variable in a C program**
  - `&x` gives us the address of `x`.
  - If `x` has type `T`, then `&x` has type `T*`.

Example data representations

C type	Size in bytes on x86-64
`char`	1
`short`	2
`int`	4
`long`	8
`pointer`	8

Byte ordering

- **So, how are the bytes within a multi-byte word ordered in memory?**
  - Most significant byte at lowest address, or least significant byte at lowest address?
- **Conventions**
  - Big endian: SPARC, POWER, Internet protocols.
    - Least significant byte has highest address (“comes last”).
  - Little endian: x86, ARM (mostly).
  - Least significant byte has highest address (“comes first”).

Byte ordering example

- **Example**
  - Variable has 4-byte value of `0x01234567`.
  - Address &x is `0x100`.
    - No matter what, the address of an object is always the address of the *first* byte in the object (counting from lowest addresses).

Big endian

		0x100	0x101	0x102	0x103		
		01	23	45	67		

Little endian

		0x100	0x101	0x102	0x103		
		67	45	23	01		

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Important note

This difference is *not visible* unless you start decomposing integers as bytes with low-level operations. Bit-shifting etc. always acts as expected.

Examining data representations

- **Code to print byte representation of data**
  - Casting pointer to `unsigned char*` allows treatment as byte array.

```
void show_bytes(unsigned char* start, size_t len) {
  size_t i;
  for (i = 0; i < len; i++)
    printf("%p\t0x%.2x\n", start+i, start[i]);
  printf("\n");
}
```

`printf` directives:

- %p: Print pointer.
- %x: Print hexadecimal.

show_bytes execution example

```
int a = 15213;
printf("int a = 15213;\n");
show_bytes((unsigned char*) &a, sizeof(int));
```

Result (Linux x86-64):

```
0x7fffb7f71dbc 6d
0x7fffb7f71dbd 3b
0x7fffb7f71dbe 00
0x7fffb7f71dbf 00
```

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Binary IO

Text IO

```
printf("Hello, world!\n");
```

Text IO

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Hello, world!
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Text IO

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int x = 123;
printf("an integer: %d\n", x);
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Text IO

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printf("Hello, world!\n");

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double y = 1.23;
printf("a float: %f\n", y);
```

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Hello, world!

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Hello, world!

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printf("a mess: %d\n", y);
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```
Hello, world!

an integer: 123

an integer:   123

a float: 1.230000

a mess: 4202562
```

Text IO

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```

```
Hello, world!

an integer: 123

an integer:   123

a float: 1.230000

a mess: 4202562
```

Make sure format specifiers and argument types match!

Text representation

- **Machines only understand numbers, and text is an abstraction!**
- E.g. when the terminal receives a byte with the value 65, it draws an A.
- `printf()` determines which *bytes* must be written to the terminal to produce the text corresponding to e.g. the number `123`: `[49, 50, 51]`.

Character sets

A character set maps a *number* to a *character*.

- ASCII defines characters in the range `0–127` (`asciitable.com`).
- Some are invisible/unprintable *control characters*
- *Unicode* is a superset of ASCII that defines tens of thousands of characters for all the world's scripts.

We'll assume ASCII, which has the simple property that 1 byte = 1 character.

The ASCII table

Control characters **Normal characters**

000	nul	016	dle	032	␣	048	0	064	@	080	P	096	‘	112	p
001	soh	017	dc1	033	!	049	1	065	A	081	Q	097	a	113	q
002	stx	018	dc2	034	“	050	2	066	B	082	R	098	b	114	r
003	etx	019	dc3	035	#	051	3	067	C	083	S	099	c	115	s
004	eot	020	dc4	036	$	052	4	068	D	084	T	100	d	116	t
005	enq	021	nak	037	%	053	5	069	E	085	U	101	e	117	u
006	ack	022	syn	038	&	054	6	070	F	086	V	102	f	118	v
007	bel	023	etb	039	'	055	7	071	G	087	W	103	g	119	w
008	bs	024	can	040	(	056	8	072	H	088	X	104	h	120	x
009	tab	025	em	041	)	057	9	073	I	089	Y	105	i	121	y
010	lf	026	eof	042	*	058	:	074	J	090	Z	106	j	122	z
011	vt	027	esc	043	+	059	;	075	K	091	[	107	k	123	{
012	np	028	fs	044	’	060	<	076	L	092	␣	108	l	124	|
013	cr	029	gs	045	-	061	=	077	M	093	]	109	m	125	}
014	so	030	rs	046	.	062	>	078	N	094	ˆ	110	n	126	˜
015	si	031	us	047	/	063	?	079	O	095	_	111	o	127	del

Turning numbers into text

```c
int x = 1234;
printf("x: %d\n", x);
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Turning numbers into text

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The text *string* that is passed to `printf()` looks like this in memory:

Characters	x	:		%	d	\n	\0
Bytes	120	58	32	37	100	10	0

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Characters	x	:		%	d	\n	\0
Bytes	120	58	32	37	100	10	0

`printf()` rewrites format specifiers (`%d`) to the textual representation of their corresponding value argument:

Characters	x	:		1	2	3	4	\n	\0
Bytes	120	58	32	49	50	51	52	10	0

These bytes (except the `0`) are then written to *standard output* (typically the terminal) which interprets them as characters and eventually draws pixels on the screen.

Machine representation versus text representation

```
int x = 305419896;
```

- Written as hexadecimal (base-16), this number is `0x12345678`.
- One hexadecimal digit is 4 bit, so each group of two digits is one byte, and the number takes four bytes (32 bits).
- The *machine representation* in memory on an x86 CPU is
  `0x78 0x56 0x34 0x12`
- A *decimal text representation* in memory on *any* CPU is
  `0x33 0x30 0x35 0x34 0x35 0x36 0x37 0x38`
- Endianness has *no effect on text* (at least not with single-byte characters).
- In C, we have the additional convention that any string must be NUL-terminated.
- We identify a string with the address of its first character.

A machine view of memory

A machine view of text

Binary IO

Writing bytes

The `fwrite` function writes raw data to an open file:

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

`ptr`: the address in memory of the data.

`size`: the size of each data element in bytes.

`nmemb`: the number of data elements.

`stream`: the target file (opened with `fopen()`).

- Returns the number of data elements written (equal to `nmemb` unless an error occurs).
- Usually no difference between writing one size `x*y` element or `x` size-`y` elements—do whatever is convenient.

Example of `fwrite()`

```c
#include <stdio.h>

int main() {
  // Open for writing ("w")
  FILE *f = fopen("output", "w");

  char c = 42;

  fwrite(&c, sizeof(char), 1, f);

  fclose(f);
}
```

- Produces a file `output`.
- File contains the byte 42, corresponding to the ASCII character `*`.
- **`char` is just an 8-bit integer type!**
  - No special "character" meaning.
  - Most Unicode characters will not fit in a single `char` (e.g. 'æ' needs 16 bits in UTF-8).
  - Name is unfortunate/historical.
  - Signedness is *implementation-defined* for historical reasons.

Another example

```c
#include <stdio.h>

int main() {
  FILE *f = fopen("output", "w");

  int x = 0x53505048;
  // Stored as 0x48 0x50 0x50 0x53

  fwrite(&x, sizeof(int), 1, f);

  fclose(f);
}
```

- Writes bytes `0x48 0x50 0x50 0x53`.
- Corresponds to ASCII characters HPPS.
- A big-endian machine would produce SPPH.
- **Don't write code that depends on this!**

Converting a non-negative integer to its ASCII representation

```
FILE *f = fopen("output", "w");
int x = 1337;                  // Number to write;
char s[10];                    // Output buffer.
int i = 10;                    // Index of last character written.
while (1) {
  int d = x % 10;              // Pick out last decimal digit.
  x = x / 10;                  // Remove last digit.
  i = i - 1;                   // Index of next character.
  s[i] = '0' + d;              // Save ASCII character for digit.
  if (x == 0) { break; }       // Stop if all digits written.
}
fwrite(&s[i], sizeof(char), 10-i, f); // Write ASCII bytes.
fclose(f);                            // Close output file.
```

Reading bytes

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

`ptr`: where to put the data we read.

`size`: the size of each data element in bytes.

`nmemb`: the number of data elements.

`stream`: the target file (opened with `fopen()`).

Very similar to `fwrite()`!

Reading all the bytes in a file

```
#include <stdio.h>
#include <assert.h>

int main(int argc, char* argv[]) {
  FILE *f = fopen(argv[1], "r");
  unsigned char c;
  while (fread(&c, sizeof(char), 1, f) == 1) {
    printf("%3d␣", (int)c);
    if (c > 31 && c < 127) {
      fwrite(&c, sizeof(char), 1, stdout);
    }
    printf("\n");
  }
}
```

Running `fread-bytes`

```
$ gcc -o fread-bytes -Wall -Wextra -pedantic fread-bytes.c
```

Running fread-bytes

```
$ gcc -o fread-bytes -Wall -Wextra -pedantic fread-bytes.c

$ ./fread-bytes fread-bytes.c
 35 #
105 i
110 n
 99 c
108 l
117 u
100 d
101 e
 32
 60 <
...
```

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```

```
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108 l
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 32
 60 <
...
```

```
$ ./fread-bytes fread-bytes
127
 69 E
 76 L
 70 F
  2
  1
  1
  0
  0
  0
...
```

Text files versus binary files

- **To the system there is no difference between “text files” and “binary files”!**
- All files are just byte sequences.
- *Colloquially*: a text file is a file that is understandable when the bytes are interpreted as characters (in ASCII or some other character set).

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Compactness of storage

- A 32-bit integer takes up to 12 bytes to store as base-10 ASCII digits
- 4 bytes as raw data
- **Raw data takes up less space and is much faster to read.**
- But we need special programs to decode the data to human-readable form.

IO summary

- Use `printf()` for text output.
- (And `scanf()` for text *input*.)
- Use `fwrite()` to write raw data.
- Use `fread()` to read raw data.
- Raw data files are more compact and faster to read/write.