Byte-oriented memory, pointers, and IO

Troels Henriksen

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

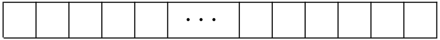
A machine view of memory

A machine view of text

Binary IO

Byte-oriented memory organisation

$00 \cdots 0_{16}$ $FF \cdots F_{16}$



- **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 variable* 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

0x0fe	0x0ff	0x100	0x101	0x102	0x103	0x104	0x105
		01	23	45	67		

Little endian

0x0fe	0x0ff	0x100	0x101	0x102	0x103	0x104	0x105
		67	45	23	01		

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

0x0fe	0x0ff	0x100	0x101	0x102	0x103	0x104	0x105
		01	23	45	67		

Little endian

0x0fe	0x0ff	0x100	0x101	0x102	0x103	0x104	0x105
		67	45	23	01		

Important note

This difference is *not visible* unless you start decomposing integers as bytes with memory 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
```

A machine view of memory

A machine view of text

Binary IO

Text IO

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

Text IO

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

```
Hello, world!
```

Text IO

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

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

```
Hello, world!
```

Text IO

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

```
Hello, world!
```

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

```
an integer: 123
```

Text IO

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

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

printf("an integer: %5d\n", x);
```

```
Hello, world!

an integer: 123
```

Text IO

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

```
Hello, world!
```

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

```
an integer: 123
```

```
printf("an integer: %5d\n", x);
```

```
an integer:   123
```

Text IO

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

```
Hello, world!
```

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

```
an integer: 123
```

```
printf("an integer: %5d\n", x);
```

```
an integer:   123
```

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

Text IO

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

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

printf("an integer: %5d\n", x);

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

```
Hello, world!

an integer: 123

an integer:   123

a float: 1.230000
```

Text IO

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

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

printf("an integer: %5d\n", x);

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

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

```
Hello, world!

an integer: 123

an integer:   123

a float: 1.230000
```

Text IO

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

```
Hello, world!
```

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

```
an integer: 123
```

```
printf("an integer: %5d\n", x);
```

```
an integer:   123
```

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

```
a float: 1.230000
```

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

```
a mess: 4202562
```

Text IO

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

```
Hello, world!
```

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

```
an integer: 123
```

```
printf("an integer: %5d\n", x);
```

```
an integer:   123
```

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

```
a float: 1.230000
```

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

```
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	^	110	n	126	~
015	si	031	us	047	/	063	?	079	O	095	_	111	o	127	del

Turning numbers into text

```
int x = 1234;
printf("x: %d\n", x);
```

Turning numbers into text

```
int x = 1234;
printf("x: %d\n", x);
```

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

Turning numbers into text

```
int x = 1234;
printf("x: %d\n", x);
```

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

`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 <
...
```

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 <
...
```

```
$ ./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).

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).

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.