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# Error-Correcting Codes

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## Instructor's Handout

This file contains solutions and notes.  
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## Part 1: Error Detection

An ISBN<sup>1</sup> is a unique identifier publishers assign to their books. It comes in two forms: ISBN-10 and ISBN-13. Naturally, ISBN-10s have ten digits, and ISBN-13s have thirteen. The final digit in both versions is a *check digit*.

Say we have a sequence of nine digits, forming a partial ISBN-10:  $n_1n_2\dots n_9$ . The final digit,  $n_{10}$ , is chosen from  $\{0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10\}$  so that:

$$\sum_{i=1}^{10} (11 - i)n_i \equiv 0 \pmod{11}$$

If  $n_{10}$  is equal to 10, it is written as X.

### Problem 1:

Only one of the following ISBNs is valid. Which one is it?

*Note:* Dashes are meaningless.

- 0-134-54896-2
- 0-895-77258-2

### Solution

The second is valid.

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<sup>1</sup>International Standard Book Number

**Problem 2:**

Take a valid ISBN-10 and change one digit.

Is it possible that you get another valid ISBN-10?

Provide an example or a proof.

**Solution**

Let  $S$  be the sum  $10n_1 + 9n_2 + \dots + 2n_9 + n_{10}$ , before any digits are changed.

If you change one digit of the ISBN,  $S$  changes by  $km$ , where  $k \in \{1, 2, \dots, 10\}$  and  $|m| \leq 10$ .  $k$  and  $m$  cannot be divisible by 11, thus  $km$  cannot be divisible by 11.

We know that  $S \equiv 0 \pmod{11}$ .

After the change, the checksum is  $S + km \equiv km \not\equiv 0 \pmod{11}$ .

**Problem 3:**

Take a valid ISBN-10 and swap two adjacent digits. This is called a *transposition error*.

When will the result be a valid ISBN-10?

**Solution**

Let  $n_1n_2\dots n_{10}$  be a valid ISBN-10.

When we swap  $n_i$  and  $n_{i+1}$ , we subtract  $n_i$  and add  $n_{i+1}$  to the checksum.

If the new ISBN is to be valid, we must have that  $n_{i+1} - n_i \equiv 0 \pmod{11}$ .

This is impossible unless  $n_i = n_{i+1}$ . Figure out why yourself.

**Definition 4:**

ISBN-13 error checking is slightly different.

Given a partial ISBN-13 with digits  $n_1n_2n_3\dots n_{12}$ , the final digit is given by

$$n_{13} = \left[ \sum_{i=1}^{12} n_i \times (2 + (-1)^i) \right] \bmod 10$$

**Problem 5:**

What is the last digit of the following ISBN-13?

978-030-7292-06\*

**Solution**

The final digit is 3.

**Problem 6:**

Take a valid ISBN-13 and change one digit. Is it possible that you get another valid ISBN-13?

If you can, provide an example; if you can't, provide a proof.

**Solution**

Let  $n_1n_2\dots n_{13}$  be a valid ISBN-13. Choose some  $n_i$  and change it to  $m_i$ .

Since  $n_i, m_i \in \{0, 1, 2, \dots, 9\}$ ,  $-9 \leq n_i - m_i \leq 9$ .

Case 0:  $i$  is 13

This is trivial.

Case 1:  $i$  is odd

For the new ISBN to be valid, we need  $n_i - m_i \equiv 0 \pmod{10}$ .

This cannot happen if  $n_i \neq m_i$ .

Case 2:  $i$  is even

For the new ISBN to be valid, we need  $3(n_i - m_i) \equiv 0 \pmod{10}$

This cannot happen, 10 and 3 are coprime.

**Problem 7:**

Take a valid ISBN-13 and swap two adjacent digits. When will the result be a valid ISBN-13?

*Hint:* The answer here is more interesting than it was last time.

**Solution**

Say we swap  $n_i$  and  $n_{i+1}$ , where  $i \in \{1, 2, \dots, 11\}$ .

The checksum changes by  $2(n_{i+1} - n_i)$ , and will remain the same if this value is  $\equiv 0 \pmod{10}$ .

**Problem 8:**

978-008-2066-466 was a valid ISBN until I changed a single digit.

Can you find the digit I changed? Can you recover the original ISBN?

**Solution**

Nope, unless you look at the meaning of each digit in the spec.

If you're unlucky, maybe not even then.

## Part 2: Error Correction

As we saw in Problem 8, the ISBN check-digit scheme does not allow us to correct errors. QR codes feature a system that does.

Odds are, you've seen a QR code with an image in the center. Such codes aren't "special"—they're simply missing their central pixels. The error-correcting algorithm in the QR specification allows us to read the code despite this damage.



### Definition 9: Repeating codes

The simplest possible error-correcting code is a *repeating code*. It works just as you'd expect: Instead of sending data once, it sends multiple copies of each bit.

If a few bits are damaged, they can be both detected and repaired.

For example, consider the following three-repeat code encoding the binary string 101:

111 000 111

If we flip any one bit, we can easily find and fix the error.

### Problem 10:

How many repeated digits do you need to...

- detect a transposition error?
- correct a transposition error?

### Definition 11: Code Efficiency

The efficiency of an error-correcting code is calculated as follows:

$$\frac{\text{number of data bits}}{\text{total bits sent}}$$

For example, the efficiency of the three-repeat code above is  $\frac{3}{9} = \frac{1}{3} \approx 0.33$

### Problem 12:

What is the efficiency of a  $k$ -repeat code?

Repeat codes are not efficient. We need to inflate our message by *three times* if we want to correct even a single error. We need a better system.



We'll now add four more parity bits, in positions 0001, 0010, 0100, and 1000:  
 This error-detection scheme is called the *Hamming code*.

X	X	X	1
X	1	0	1
X	1	0	1
1	0	0	1

Bit 0001 will count the parity of all bits with a one in the first digit of their index.  
 Bit 0010 will count the parity of all bits with a one in the second digit of their index.  
 Bits 0100 and 1000 work in the same way.

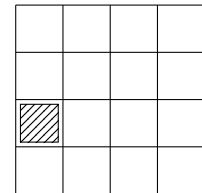
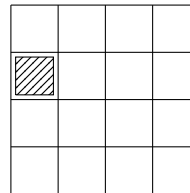
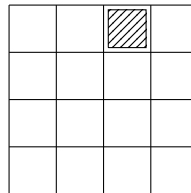
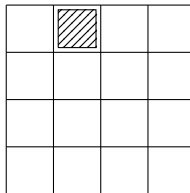
*Hint:* In 0001, 1 is the first digit. In 0010, 1 is the second digit.  
 When counting bits in binary numbers, go from right to left.

**Problem 17:**

Which message bits does each parity bit “cover”?

In other words, which message bits affect the value of each parity bit?

Four diagrams are shown below. In each grid, fill in the bits that affect the shaded parity bit.



**Problem 18:**

Compute all parity bits in the message above.

**Problem 19:**

Analyze this coding scheme.

- Can we detect one single-bit errors?
- Can we detect two single-bit errors?
- What errors can we correct?

**Problem 20:**

Each of the following messages has either one, two, or no errors.

Find the errors and correct them if possible.

*Hint:* Bit 0000 should tell you how many errors you have.

0	1	1	1
0	1	1	1
0	0	1	1
1	1	1	0

1	1	0	1
1	0	1	0
0	1	1	0
1	1	0	1

0	1	1	1
1	0	1	1
1	0	1	1
1	0	0	0

**Solution**

- 1: Single error at position 1010
- 2: Double error
- 3: No error

**Problem 21:**

How many parity bits does each message bit affect?  
Does this correlate with that message bit's index?

**Problem 22:**

Say we have a message with exactly one single-bit error.  
If we know which parity bits are inconsistent, how can we find where the error is?

**Problem 23:**

Generalize this system for messages of 4, 64, or 256 bits.

- How does the resilience of this scheme change if we use a larger message size?
- How does the efficiency of this scheme change if we send larger messages?

**Definition 24:**

A *deletion* error occurs when one bit of the message is deleted. Likewise, an *insertion* error consists of a random inserted bit.

**Definition 25:**

A *message stream* is an infinite string of binary digits.

**Problem 26:**

Show that Hamming codes do not reliably detect bit deletions:

*Hint:* Create a 17-bit message whose first 16 bits are a valid Hamming-coded message, and which is still valid when a bit (chosen by you; not the 17<sup>th</sup>) is deleted.

**Problem 27:**

Convince yourself that Hamming codes cannot correct insertions.

Then, create a 16-bit message that:

- is itself a valid Hamming code, and
- incorrectly "corrects" a single bit error when it encounters an insertion error.

You may choose where the insertion occurs.

As we have seen, Hamming codes effectively handle substitutions, but cannot reliably detect (or correct) insertions and deletions. Correcting those errors is a bit more difficult: if the number of bits we receive is variable, how can we split a stream into a series of messages?

This is a rhetorical question, which we'll discuss another day.