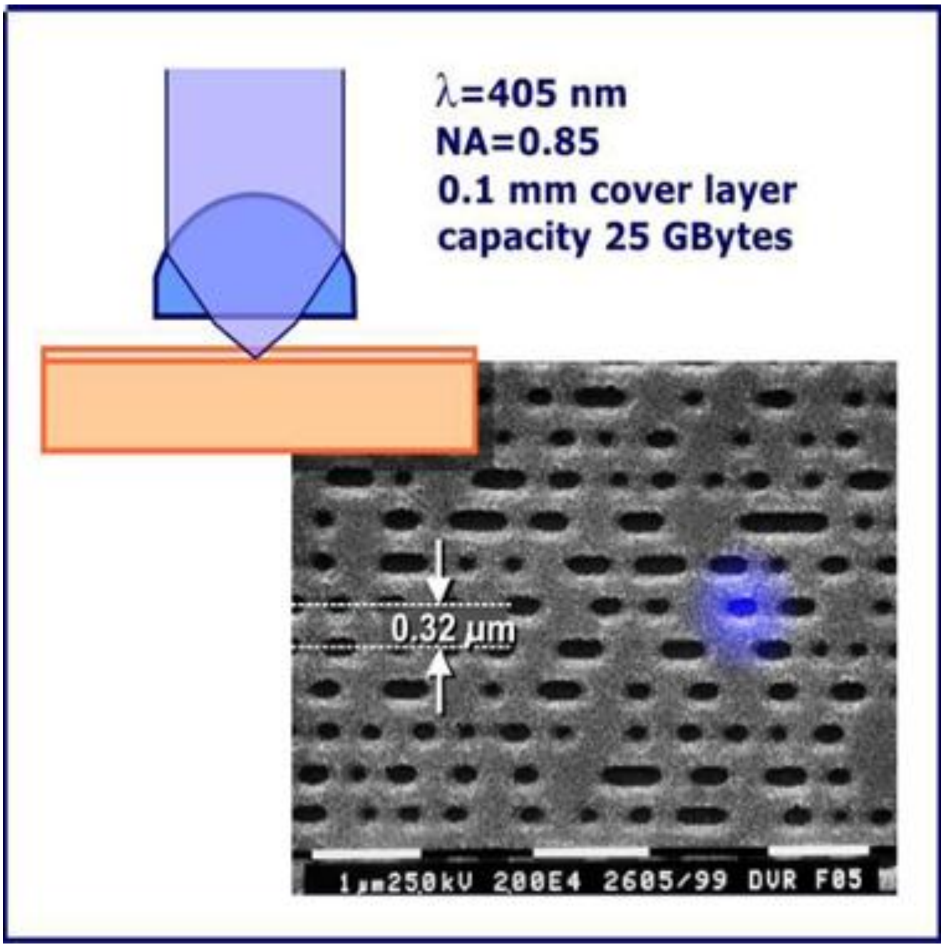
The Blu-ray Disc



Teacher's manual

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Many parties were involved in making this project available for schools:

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Jet-Net, the Dutch Youth and Technology Network, is a partnership between companies, education and government. The aim is to provide higher general secondary school (HAVO) and pre-university school (VWO) pupils with a true picture of science and technology and to interest them in a scientific-technological higher education course.

European Schoolnet (EUN) is a network of 30 Ministries of Education in Europe and beyond. EUN was created to bring innovation in teaching and learning to its key stakeholders: Ministries of Education, schools, teachers and researchers. The 'Ingenious' project is coordinated by European Schoolnet.

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ERT is a forum bringing together around 45 chief executives and chairmen of multinational industrial and technological companies with European heritage with sales volume exceeding € 1,000 billion and thereby sustaining around 6.6 million jobs in Europe. ERT advocates policies at both national and European levels which help create conditions necessary to improve European growth and jobs. ERT was the initiating force for the EU Coordinating Body (ECB), now called 'Ingenious', to disseminate proven best practices of industry-school cooperation to stimulate interest in careers in science and technology throughout the European Member States.

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TEACHER'S MANUAL FOR
The Blu-ray Disc

STRUCTURE OF TEACHING MATERIAL

This teaching package introduces students to the principles underlying the Blu-ray Disc. It also demonstrates that developments such as these are only possible as a result of co-operation between specialist fields. The teaching material covers a number of these fields in various modules.

The teaching material consists of six components:
1. Introduction
2. Module 1: From analogue to digital (electrical engineering)
3. Module 2: Locating and correcting errors (maths and IT)
4. Module 3: Reading and writing with light (physics)
5. Module 4: Focusing and tracking (measurement and control engineering, electrical engineering)
6. DVD with support material

DESCRIPTION OF THE COMPONENTS

The *Introduction* is a short general foreword about recording, storing and sending data.

In *Module 1* students are given an idea of how to convert a music or video signal into a digital signal that you can write to an optical disc (CD, DVD, Blu-ray disc). This is done by following the steps music signal -> decimal number -> binary number.

Module 2 shows which mathematical methods you can use to correct playback errors (for instance due to dust particles, scratches, etc.). A Blu-ray player cannot see whether there is a scratch or a bit of dirt on the disc, but only reads 0s and 1s. The player doesn't know whether they are right or wrong, but mathematical methods can check this *and* correct it if necessary.

In *Module 3* students learn how to record a signal physically on a plastic disc using 0s and 1s. How much space is there on a disc and how can you utilise it as efficiently as possible? The wavelength of laser light, optical possibilities and impossibilities and timing play a part in this.

Module 4 shows what problems you come up against if you want to read a weaving track using a tiny laser beam. This is solved with tracking systems that use the Lorentz force.

The support films illustrate what goes on inside a Blu-ray player.

Film 1. Provides a glimpse under 'the bonnet' and introduces the 1:10 scale model of the player which will later be used to demonstrate how it operates.
Film 2. Shows the components that make up the read unit and the path that the laser beam takes from the source, via the disc, to a light-sensitive sensor.
Film 3. Shows the components that make up the tracking system that enables the laser beam to follow the weaving movements of the disc.
Film 4. Shows a rotating disc with pits and how the tracking system follows the weaving movement of the disc.
Film 5. Shows how the intensity of the reflected light determines whether a 0 or a 1 is read.
Film 6. Is an animation showing how data is written to a Blu-ray Disc.

Films 1 to 4 link up with the material in Module 4, 'Focusing and tracking'. Films 5 and 6 can then be shown subsequently, but they also fit in with the material in Module 3, 'Reading and writing with light'.

ANSWERS TO THE ASSIGNMENTS

Assignment 2

0101 $= \mathbf{0} \times 2^3 + \mathbf{1} \times 2^2 + \mathbf{0} \times 2^1 + \mathbf{1} \times 2^0 = 4 + 1 = 5$

0011 $= \mathbf{0} \times 2^3 + \mathbf{0} \times 2^2 + \mathbf{1} \times 2^1 + \mathbf{1} \times 2^0 = 2 + 1 = 3$

1000 $= \mathbf{1} \times 2^3 + \mathbf{0} \times 2^2 + \mathbf{0} \times 2^1 + \mathbf{0} \times 2^0 = 8$

1111 $= \mathbf{1} \times 2^3 + \mathbf{1} \times 2^2 + \mathbf{1} \times 2^1 + \mathbf{1} \times 2^0 = 8 + 4 + 2 + 1 = 15$

0000 $= \mathbf{0} \times 2^3 + \mathbf{0} \times 2^2 + \mathbf{0} \times 2^1 + \mathbf{0} \times 2^0 = 0$

Fill in:

1100 $= \mathbf{1} \times 2^3 + \mathbf{1} \times 2^2 + \mathbf{0} \times 2^1 + \mathbf{0} \times 2^0 = 8 + 4 = 12$

0111 $= \mathbf{0} \times 2^3 + \mathbf{1} \times 2^2 + \mathbf{1} \times 2^1 + \mathbf{1} \times 2^0 = 4 + 2 + 1 = 7$

10 $= 1 \times 8 + 0 \times 4 + 1 \times 2 + 0 \times 1 = \mathbf{1} \times 2^3 + \mathbf{0} \times 2^2 + \mathbf{1} \times 2^1 + \mathbf{0} \times 2^0 = \mathbf{1\ 0\ 1\ 0}$

4 $= 0 \times 8 + 1 \times 4 + 0 \times 2 + 0 \times 1 = \mathbf{0} \times 2^3 + \mathbf{1} \times 2^2 + \mathbf{0} \times 2^1 + \mathbf{0} \times 2^0 = \mathbf{0\ 1\ 0\ 0}$

Always find the highest power of 2 that fits in the number (or the remainder), e.g.:

$37 = 32 + [5] = 32 + 4 + [1] = 32 + 4 + 1 = 2^5 + 2^2 + 2^0 = 1\ 0\ 0\ 1\ 0\ 1$ = in bytes: 0 0 1 0 0 1 0 1
(add 0s on the left until a total of 8 bits is reached: 1 byte = 8 bits).

$53 = 32 + [21] = 32 + 16 + [5] = 32 + 16 + 4 + [1] = 32 + 16 + 4 + 1 = 2^5 + 2^4 + 2^2 + 2^0 = 1\ 1\ 0\ 1\ 0\ 1$
= in bytes: 0 0 1 1 0 1 0 1

Assignment 3

A 4-bit number can have a total of **16** different values: 0, 1, 2, …, 14, 15.

So the range from -4V to +4V can be divided into 16 intervals, with a step size of 8V/16=0.5V.

Assignment 4

For the audio CD a bit depth or resolution of 16 bits is used. The largest power of 2 for a 16-bit number is $2^{15} = 32768$.

The smallest 16-bit number is 0000 0000 0000 0000 = 0
The largest 16-bit number is 1111 1111 1111 1111 = $2^{16} – 1 = 65535$.
A 16-bit number can therefore have 65536 = 2^{16} different values.

Assignment 5

1000 1000 1000 = $1 \times 2^{11} + 1 \times 2^{7} + 1 \times 2^{3} = 2048 + 128 + 8 = 2184$.

0101 0101 0101 = $1 \times 2^{10} + 1 \times 2^{8} + 1 \times 2^{6} + 1 \times 2^{4} + 1 \times 2^{2} + 1 \times 2^{0} = 1024 + 256 + 64 + 16 + 4 + 1 = 1365$.

0000 0000 1010 = $1 \times 2^{3} + 1 \times 2^{1} = 8 + 2 = 10$.

1000 0000 0001 = $1 \times 2^{11} + 1 \times 2^{0} = 2048 + 1 = 2049$.

Assignment 6

4095 = 2048 + [2047] =
= 2048 + [1024] + 1023 =
= 2048 + 1024 + 512 + [511] =
= 2048 + 1024 + 512 + 256 + [255] =
= 2048 + 1024 + 512 + 256 + 128 + [127] =
= 2048 + 1024 + 512 + 256 + 128 + 64 + [63] =
= 2048 + 1024 + 512 + 256 + 128 + 64 + 32 + [31] =
= 2048 + 1024 + 512 + 256 + 128 + 64 + 32 + 16 + [15] =
= 2048 + 1024 + 512 + 256 + 128 + 64 + 32 + 16 + 8 + [7] =
= 2048 + 1024 + 512 + 256 + 128 + 64 + 32 + 16 + 8 + 4 + [3] =
= 2048 + 1024 + 512 + 256 + 128 + 64 + 32 + 16 + 8 + 4 + 2 + [1] =
= 2048 + 1024 + 512 + 256 + 128 + 64 + 32 + 16 + 8 + 4 + 2 + 1 = **1111 1111 1111**

3000 = 2048 + [952] =
= 2048 + 512 + [440] =
= 2048 + 512 + 256 + [184] =
= 2048 + 512 + 256 + 128 + [56] =
= 2048 + 512 + 256 + 128 + 32 + [24] =
= 2048 + 512 + 256 + 128 + 32 + 16 + [8] =
= 2048 + 512 + 256 + 128 + 32 + 16 + 8 + [0] = **1011 1011 1000**

199 = 128 + [71] =
= 128 + 64 + [7] =
= 128 + 64 + 4 + [3] =
= 128 + 64 + 4 + 2 + [1] =
= 128 + 64 + 4 + 2 + 1 + [0] = **0000 1100 0111**

1234 = 1024 + [210] =
= 1024 + 128 + [82] =
= 1024 + 128 + 64 + [18] =
= 1024 + 128 + 64 + 16 + [2] =
= 1024 + 128 + 64 + 16 + 2 + [0] = **0100 1101 0010**

Assignment 7

Volts scale of -4 to +4 V	**Volts** scale of 0 to 8 V	**Decimal number**	**Binary number**
-2.21	1.79	916	0011 1001 0100
1.03	5.03	2575	1010 0000 1111
0.73	4.73	2421	1001 0111 0101
-1.51	2.49	1275	0100 1111 1011
0.67	4.67	2390	1001 0101 0110
-0.28	3.72	1904	0111 0111 0000
-1.88	2.12	1085	0100 0011 1101

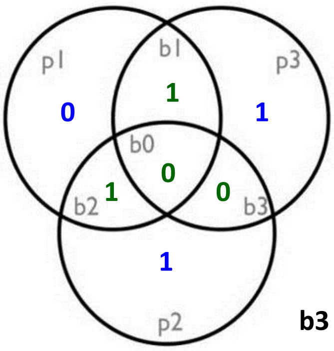
-2.21 V <-> 1.79 V <-> (1.79 / 8) * 4095 = 916.26 <-> 916
1.03 V <-> 5.03 V <-> (5.03 / 8) * 4095 = 2574.73 <-> 2575

Assignment 8

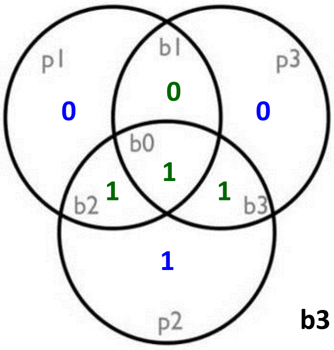
Take the text "ABC": use the enclosed ASCII table (Annexe A, "Binary" worksheet)

text:	A	B	C
text to decimal:	101	102	103
decimal to binary:	0 1 0 0 0 0 0 1	0 1 0 0 0 0 1 0	0 1 0 0 0 0 1 1

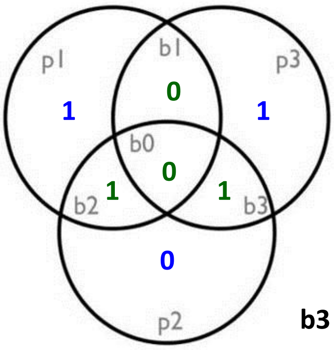
Assignment 9



b3 b2 b1 b0 = 0110 -> p3 p2 p1 = 110



b3 b2 b1 b0 = 1101 -> p3 p2 p1 = 010



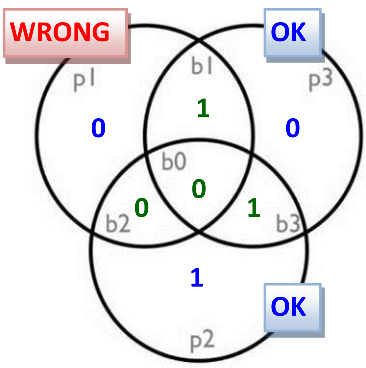
b3 b2 b1 b0 = 1100 -> p3 p2 p1 = 101

After being encoded with the Hamming code, the 12-bit music fragment **1100 0110 1101 1100** looks like this: **1100101 0110110 1101010 1100101**.

Assignment 10

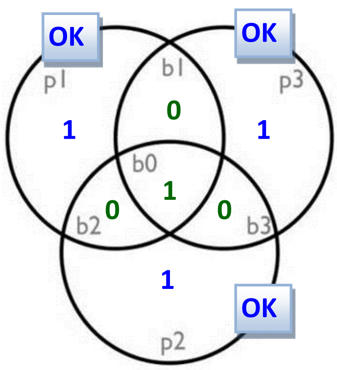
Code word 1010010 -> b3 b2 b1 b0 = **1010**; p3 p2 p1 = **010**

No valid code word: the top-left circle contains an odd number of 1s!



Code word 0001111 -> b3 b2 b1 b0 = **0001**; p3 p2 p1 = **111**

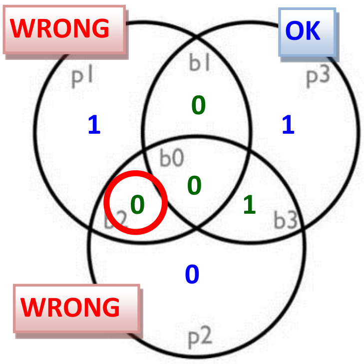
Valid code word: all circles contain an even number of 1s!

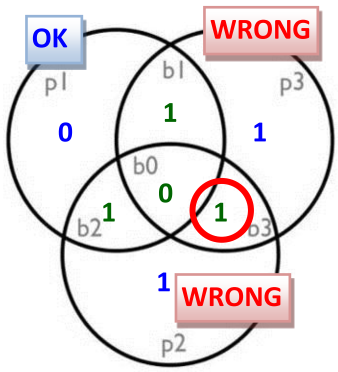


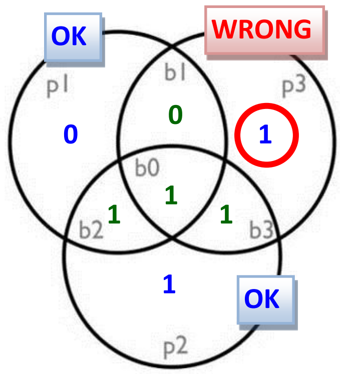
Assignment 11

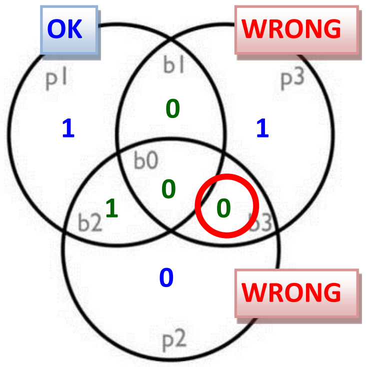
After reading the CD we get the following series of bits:

1000101111011011011100100101 =
1000101 1110110 1101110 0100101 =
1000 101 1110 110 1101 110 0100 101









So the wrong bits in the read sequence are:

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

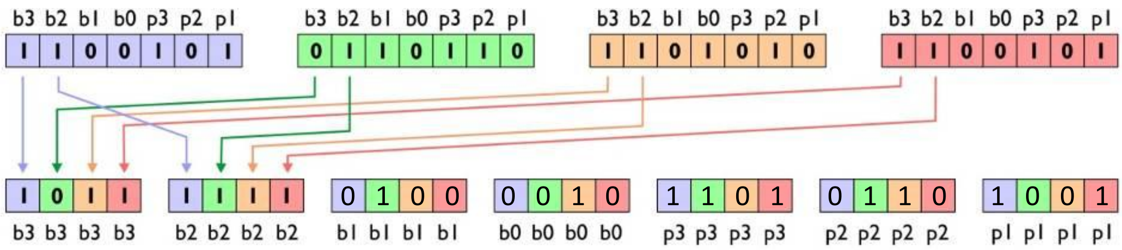
After correction (0 becomes 1 and 1 becomes 0), this gives:

1 1 0 0 1 0 1 0 1 1 0 1 1 0 1 1 0 1 0 1 0 1 1 0 0 1 0 1,

with the user bits being: **1100 0110 1101 1100**, and this is indeed equal to the original sequence of bits as defined at the bottom of page 17.

Assignment 12

After interleaving, the series of bits in assignment 9, **1100101 0110110 1101010 1100101**, looks like this:



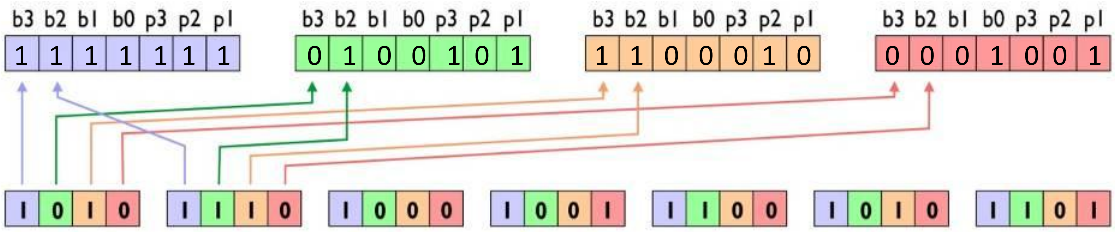
So the requested series of bits after interleaving is:

1011 1111 0100 0010 1101 0110 1001

Assignment 13

Take the following series of bits that has been read **to** disc with interleaving:
1010 1110 1000 1001 1100 1010 1101

This series of bits consists of the following 4 code words: **1111111 0100101 1100010 0001001**



Assignment 15

The laser spot diameter w is given by w = 1.22 x λ / NA, with λ being the wavelength of the laser light and NA the numerical aperture of the objective lens that focuses the light.

w_{CD} = 1.22 x 780 nm / 0.45 = 2115 nm = 2.12 μm

w_{DVD} = 1.22 x 650 nm / 0.60 = 1322 nm = 1.32 μm

$w_{Blu\text{-}ray\ Disc}$ = 1.22 x 405 nm / 0.85 = 581 nm = 0.58 μm

The surface area of the laser spots is $O_w = \pi \times (w/2)^2$

$O_{w, CD}$ = 3.14 x 1.06^2 μm^2 = 3.5 μm^2

$O_{w, DVD}$ = 3.14 x 0.66^2 μm^2 = 1.4 μm^2

$O_{w, Blu\text{-}ray\ Disc}$ = 3.14 x 0.29^2 μm^2 = 0.26 μm^2

The surface area of the actively used part of the disc, between radii R_{in}=22mm and R_{out}=58mm, is
$O_{disc} = \pi \times R_{out}^2 - \pi \times R_{in}^2 = \pi \times (R_{out}^2 - R_{in}^2) = 3.14 \times (58^2\text{-}22^2)\ mm^2 = 9048\ mm^2$; or:
$O_{disc} = 9.048 \times 10^3\ mm^2 = 3.048 \times 10^9\ \mu m^2$.

The total number of available bits can now be calculated by dividing the active disc surface area by the surface area of the laser spot O_w:

Number of CD bits = O_{disc} / $O_{w, CD}$ = 3.048 x 10^9 / 3.5 = 870857142 = 871 x 10^6 bits

Number of DVD bits = O_{disc} / $O_{w, DVD}$ = 3.048 x 10^9 / 1.4 = 2177142857 = 2177 x 10^6 bits

Number of Blu-ray Disc bits = O_{disc} / $O_{w, Blu\text{-}ray\ Disc}$ = 3.048 x 10^9 / 0.26 = 11723076923 = 11723 x 10^6 bits

Note:
This is only a rough approximation. The number of bits calculated here differs from the number of bits actually available because:
(i) in these calculations the channel bit length should actually be taken (Chapter 3);
(ii) the actual number of bits is obtained by dividing the length of the data spiral by the physical length of a channel bit. See assignments 19 and 20. The track distance is involved here, which has been minimised for the various systems (CD, DVD and Blu-ray Disc) in such a way as to be able to read the signals with just enough signal-noise ratio and minimum *cross-talk* (= the effect of track *n*-1 and track *n*+1 on the track to be read, *n*).

Assignment 16

A music CD has a playback time of 74 minutes.	This is **4440** sec.
The music is sampled at 44100 samples/sec.	So for 74 min of music **195804000** samples are required.
For stereo sound two channels are recorded simultaneously.	So altogether we have **391608000** samples.
The resolution at which the samples are written to the disc is 16 bits/sample.	This gives a total of **6265728000** bits.
1 byte = 8 bits	This corresponds to **783216000** bytes.
1 kbyte = 1024 bytes 1 Mbyte = 1024 kbytes (so 1 MB = 1 Mbyte = 1024^2 bytes)	Storing 74 minutes of music on a CD therefore requires **783216000 bytes** / 1024^2 = **747** MB of storage capacity.

Assignment 17

The film lasts for 1 hour.	This is **3600** sec.
A film is played back at 25 frames/sec.	This gives **90000** frames.
Each frame consists of 576 lines of 720 pixels each: the dimensions for the current PAL TV system.	In total, then, there are 90000 x 576 x 720 = **37324800000** pixels.
The resolution at which the brightness of a single pixel is written to the disc is 8 bits/pixel.	This gives a total of **298598400000** bits.
For each pixel you have three colours: red, green and blue	In total, then, there are **895795200000** bits.
1 byte = 8 bits	This equals **111974400000** bytes.
1 kbyte = 1024 bytes 1 Mbyte = 1024 kbytes 1 Gbyte = 1024 Mbytes (so 1 GB =1 Gbyte = 1024^3 bytes)	Storing 1 hour of film therefore requires **111974400000 bytes** / 1024^3 = **104** GB of storage capacity.

Assignment 18

100,000 books x 300 pages/book x 4000 letters/page = 120000000000 letters = 120 x 10^9 letters.
For a single letter 1 byte of storage capacity is required: 120 x 10^9 bytes.
If we use ZIP data compression, the required number of bytes is reduced to
0.15 x 120 x 10^9 bytes = 18 x 10^9 bytes = 18 x 10^9 / 1024^3 GBytes = 16.8 GBytes.
A single Blu-ray Disc has a storage capacity of 25 GBytes. This means that we can easily put all 100,000 books on a single Blu-ray Disc!!!

Assignment 19

The total length ***L*** of the data spiral is given approximately by: $L = \pi \times (R_{out}^2 - R_{in}^2) / p$. R_{out} = 58mm; R_{in}= 22mm; p_{CD}= 1.6μm; p_{dvd}=0.74μm and $p_{Blu\text{-}ray\ Disc}$= 0.32μm. Filling in the values (take care to use the correct units: 1 μm $= 10^{-3}$ mm) gives:

L_{CD} = 3.14 x (58^2-22^2) mm^2 / (1.6 x 10^{-3} mm) = 5654867 mm = 5654 m = 5.6 km

L_{DVD} = 3.14 x (58^2-22^2) mm^2 / (0.74 x 10^{-3} mm) = 12226739 mm = 12226 m = 12.2 km

$L_{Blu\text{-}ray\ Disc}$ = 3.14 x (58^2-22^2) mm^2 / (0.32 x 10^{-3} mm) = 28274334 mm = 28274 m = 28.3 km

Assignment 20

The total length of the data spiral on a Blu-ray Disc is 28.3 km (assignment 19). The physical length of a single channel bit for the Blu-ray Disc is 75 nm. The total number of channel bits that we can write along the spiral is then: 28.3 km / 75 nm = 28.3 x 10^3 m / (75 x 10^{-9} m) = 377333333333 bits = 47166666667 bytes = 43.9 GBytes.

Note:
This is the total number of channel bits! In practice the end user only has a certain percentage of this number of channel bits available, since some of them are needed for writing the error correction parity bits, timing information, the table of contents, etc. For the Blu-ray Disc system the consumer has 57% of the total number of channel bits available = 25 GBytes (user data).

Assignment 21

(i) The following series of 46 user bits 1010100101100000010010111101000100101110010110 is converted using 17-channel coding into a series of channel bits as follows:

user bits:	channel bits:
10	001
10	001
1001	010 000
01	100
1000	001 000
0001	100 000
00	101
10	001
11	010
11	010
01	100
0001	100 000
00	101
10	001
11	010
1001	010 000
01	100
10	001

If we place the channel bits one behind the other, we get:

001 001 010 000 100 001 000 100 000 101 001 010 010 100 100 000 101 001 010 010 000 100 001

(ii) We can calculate the run lengths in cycles by counting the number of 0s between two consecutive 1s and adding 1 to this figure:

001	001	01	00001	00001	0001	000001	01	001	01	001	01	001	000001	01	001	01	001	00001	00001
3T	3T	2T	5T	5T	4T	6T	2T	3T	2T	3T	2T	3T	6T	2T	3T	2T	3T	5T	5T

(iii) This run length sequence 3-3-2-5-5-4-6-2-3-2-3-2-3-6-2-3-2-3-5-5 is written to disc as channel bits in the form of a pit with a length of 3 cycles, a non-pit with a length of 3 cycles, a pit with a length of 2 cycles, a non-pit with a length of 5 cycles, etc. (a *non-pit* means the empty space between two consecutive pits).

This requires a total of 3+3+2+5+5+4+6+2+3+2+3+2+3+6+2+3+2+3+5+5 = 69 channel bits with a length of T. Since T equals 0.5a (with 'a' being the minimum pit size), we need a part of the data spiral for this, with a length of 69 x 0.5a = 34.5a.

Without channel coding we have to write 46 bits, each with a minimum length of a: 46a.

So by using channel coding we require 100% x (46-34.5)/46 = 25% less disc space!!