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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This technology project was originally developed by Philips (The Netherlands) for the Dutch Jet-Net-project and incorporated in the EU 'Ingenious' project of European Schoolnet (EUN).

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This document is supported by the European Union’s Framework Programme for Research and Development (FP7) – project ECB: European Coordinating Body in Maths, Science and Technology (Grant agreement Nº 266622). The content of this document is the sole responsibility of the Consortium Members and it does not represent the opinion of the European Union and the European Union is not responsible or liable for any use that might be made of information contained herein.

This is a publication of: Philips Human Resources Benelux / Jet-Net, PO Box 80003, 5600 JZ Eindhoven, The Netherlands

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Edition: English version 2.0, September 2012

for European Schoolnet ‘Ingenious’ programme 2-1-2012

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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 = 0 × 2^3 + 1 × 2^2 + 0 × 2^1 + 1 × 2^0 = 4 + 1 = 5

0011 = 0 × 2^3 + 0 × 2^2 + 1 × 2^1 + 1 × 2^0 = 2 + 1 = 3

1000 = 1 × 2^3 + 0 × 2^2 + 0 × 2^1 + 0 × 2^0 = 8

1111 = 1 × 2^3 + 1 × 2^2 + 1 × 2^1 + 1 × 2^0 = 8 + 4 + 2 + 1 = 15

0000 = 0 × 2^3 + 0 × 2^2 + 0 × 2^1 + 0 × 2^0 = 0

Fill in:

1100 = 1 × 2^3 + 1 × 2^2 + 0 × 2^1 + 0 × 2^0 = 8 + 4 = 12

0111 = 0 × 2^3 + 1 × 2^2 + 1 × 2^1 + 1 × 2^0 = 4 + 2 + 1 = 7

10 = 1 × 8 + 0 × 4 + 1 × 2 + 0 × 1 = 1 × 2^3 + 0 × 2^2 + 1 × 2^1 + 0 × 2^0 = 1 0 1 0

4 = 0 × 8 + 1 × 4 + 0 × 2 + 0 × 1 = 0 × 2^3 + 1 × 2^2 + 0 × 2^1 + 0 × 2^0 = 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

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

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

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

<table>
<thead>
<tr>
<th>text:</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>text to decimal:</td>
<td>101</td>
<td>102</td>
<td>103</td>
</tr>
<tr>
<td>decimal to binary:</td>
<td>01000001</td>
<td>01000010</td>
<td>01000011</td>
</tr>
</tbody>
</table>

Assignment 9

![Venn Diagram]

b3 b2 b1 b0 = 0110 -> p3 p2 p1 = 110
After being encoded with the Hamming code, the 12-bit music fragment \(1100\ 0110\ 1101\ 1100\) looks like this: \(1100\ 101\ 0110\ 110\ 1101\ 010\ 1100\ 101\).

**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:

\[1000101111011011100100101 = 1000 101 1110 110 1101 110 0100 101\]

So the wrong bits in the read sequence are:

\[1000 101 1110 110 1101 110 0100 101\]

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

\[1100 101 0110 110 1101 010 1100 101\]

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: \(1111111\) \(0100101\) \(1100010\) \(0001001\)

So the requested series of bits after interleaving is:

\[1010 \ 1110 \ 1000 \ 1001 \ 1100 \ 1010 \ 1101\]
Assignment 15

The laser spot diameter \(w\) is given by \(w = 1.22 \times \frac{\lambda}{NA}\), with \(\lambda\) being the wavelength of the laser light and \(NA\) the numerical aperture of the objective lens that focuses the light.

\[
\begin{align*}
    w_{\text{CD}} &= 1.22 \times 780 \text{ nm} / 0.45 = 2115 \text{ nm} = 2.12 \mu\text{m} \\
    w_{\text{DVD}} &= 1.22 \times 650 \text{ nm} / 0.60 = 1322 \text{ nm} = 1.32 \mu\text{m} \\
    w_{\text{Blu-ray Disc}} &= 1.22 \times 405 \text{ nm} / 0.85 = 581 \text{ nm} = 0.58 \mu\text{m}
\end{align*}
\]

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

\[
\begin{align*}
    O_{w, \text{CD}} &= 3.14 \times 1.06^2 \mu\text{m}^2 = 3.5 \mu\text{m}^2 \\
    O_{w, \text{DVD}} &= 3.14 \times 0.66^2 \mu\text{m}^2 = 1.4 \mu\text{m}^2 \\
    O_{w, \text{Blu-ray Disc}} &= 3.14 \times 0.29^2 \mu\text{m}^2 = 0.26 \mu\text{m}^2
\end{align*}
\]

The surface area of the actively used part of the disc, between radii \(R_{\text{in}}=22\text{mm}\) and \(R_{\text{out}}=58\text{mm}\), is

\[
O_{\text{disc}} = \pi x R_{\text{out}}^2 - \pi x R_{\text{in}}^2 = \pi x ( R_{\text{out}}^2 - R_{\text{in}}^2 ) = 3.14 x (58^2-22^2) \text{ mm}^2 = 9048 \text{ mm}^2 ; \text{ or:}
\]

\[O_{\text{disc}} = 9.048 \times 10^3 \text{ mm}^2 = 3.048 \times 10^9 \mu\text{m}^2.\]

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 \(O_w\):

\[
\begin{align*}
    \text{Number of CD bits} &= \frac{O_{\text{disc}}}{O_{w, \text{CD}}} = \frac{3.048 \times 10^9}{3.5} = 870857142 = 871 \times 10^6 \text{ bits} \\
    \text{Number of DVD bits} &= \frac{O_{\text{disc}}}{O_{w, \text{DVD}}} = \frac{3.048 \times 10^9}{1.4} = 2177142857 = 2177 \times 10^6 \text{ bits} \\
    \text{Number of Blu-ray Disc bits} &= \frac{O_{\text{disc}}}{O_{w, \text{Blu-ray Disc}}} = \frac{3.048 \times 10^9}{0.26} = 11723076923 = 11723 \times 10^6 \text{ bits}
\end{align*}
\]

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

<table>
<thead>
<tr>
<th>Description</th>
<th>Calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>A music CD has a playback time of 74 minutes.</td>
<td>This is 4440 sec.</td>
</tr>
<tr>
<td>The music is sampled at 44100 samples/sec.</td>
<td>So for 74 min of music 195804000 samples are required.</td>
</tr>
<tr>
<td>For stereo sound two channels are recorded simultaneously.</td>
<td>So altogether we have 391608000 samples.</td>
</tr>
<tr>
<td>The resolution at which the samples are written to the disc is 16 bits/sample.</td>
<td>This gives a total of 6265728000 bits.</td>
</tr>
<tr>
<td>1 byte = 8 bits</td>
<td>This corresponds to 783216000 bytes.</td>
</tr>
<tr>
<td>1 kbyte = 1024 bytes</td>
<td>Storing 74 minutes of music on a CD therefore requires 783216000 bytes / 1024² = 747 MB of storage capacity.</td>
</tr>
<tr>
<td>1 Mbyte = 1024 kbytes</td>
<td>(so 1 MB = 1 Mbyte = 1024² bytes)</td>
</tr>
<tr>
<td>The film lasts for 1 hour.</td>
<td>This is 3600 sec.</td>
</tr>
<tr>
<td>A film is played back at 25 frames/sec.</td>
<td>This gives 90000 frames.</td>
</tr>
<tr>
<td>Each frame consists of 576 lines of 720 pixels each: the dimensions for the current PAL TV system.</td>
<td>In total, then, there are 90000 x 576 x 720 = 37324800000 pixels.</td>
</tr>
<tr>
<td>The resolution at which the brightness of a single pixel is written to the disc is 8 bits/pixel.</td>
<td>This gives a total of 298598400000 bits.</td>
</tr>
<tr>
<td>For each pixel you have three colours: red, green and blue</td>
<td>In total, then, there are 895795200000 bits.</td>
</tr>
<tr>
<td>1 byte = 8 bits</td>
<td>This equals 111974400000 bytes.</td>
</tr>
<tr>
<td>1 kbyte = 1024 bytes</td>
<td>Storing 1 hour of film therefore requires 111974400000 bytes / 1024³ = 104 GB of storage capacity.</td>
</tr>
<tr>
<td>1 Mbyte = 1024 kbytes</td>
<td>(so 1 GB = 1 Gbyte = 1024³ bytes)</td>
</tr>
</tbody>
</table>
Assignment 18

100,000 books x 300 pages/book x 4000 letters/page = 1200000000 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: $L = \pi \times (R_{out}^2 - R_{in}^2) / p$.

$R_{out} = 58$ mm; $R_{in} = 22$ mm; $p_{CD} = 1.6 \mu$m; $p_{DVD} = 0.74 \mu$m and $p_{Blu-ray Disc} = 0.32 \mu$m. Filling in the values (take care to use the correct units: $1 \mu$m = $10^{-3}$ mm) gives:

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

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

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

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 = 471666666667 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 1010100110000010010111010001001011100110 is converted using 17-channel coding into a series of channel bits as follows:

<table>
<thead>
<tr>
<th>user bits:</th>
<th>channel bits:</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>001</td>
</tr>
<tr>
<td>10</td>
<td>001</td>
</tr>
<tr>
<td>1001</td>
<td>010 000</td>
</tr>
<tr>
<td>01</td>
<td>100</td>
</tr>
<tr>
<td>1000</td>
<td>001 000</td>
</tr>
<tr>
<td>0001</td>
<td>100 000</td>
</tr>
<tr>
<td>00</td>
<td>101</td>
</tr>
<tr>
<td>10</td>
<td>001</td>
</tr>
<tr>
<td>11</td>
<td>010</td>
</tr>
<tr>
<td>11</td>
<td>010</td>
</tr>
<tr>
<td>01</td>
<td>100</td>
</tr>
<tr>
<td>0001</td>
<td>100 000</td>
</tr>
<tr>
<td>00</td>
<td>101</td>
</tr>
<tr>
<td>10</td>
<td>001</td>
</tr>
<tr>
<td>11</td>
<td>010</td>
</tr>
<tr>
<td>1001</td>
<td>010 000</td>
</tr>
<tr>
<td>01</td>
<td>100</td>
</tr>
<tr>
<td>10</td>
<td>001</td>
</tr>
</tbody>
</table>

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

(iii) This run length sequence 3-3-2-5-5-4-6-2-3-2-3-6-2-3-2-3-5-5 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!!