

# 數位電路設計 (Digital Circuit Design)

## Lab2：組合電路之 HDL 模組撰寫與測試

### (Writing and Testing the HDL Modules of Combinational Circuits)

#### 1. 目標 (Goal)

在這次 Lab 中，我們希望同學們可以熟悉組合電路的設計原理，以 **gate-level modeling**、**dataflow modeling**、**behavioral modeling** 等不同方式撰寫其 HDL 電路模組，並撰寫測試模組。我們以減法器及解碼器為設計實例，分別模擬後，繳交模組檔案與波形圖。

The main purpose of this Lab Unit is to be familiar with the design of Combinational Circuits. Please write their HDL circuit modules by gate-level modeling, dataflow modeling, and behavioral modeling, and write the testbench for these circuit modules. We take binary subtractor and BCD-to-seven-segment decoder for practice. After simulation, upload the files of the modules and the waveforms of the simulation results.

#### 2. 撰寫 HDL 電路模組與測試模組 (Design of the HDL Circuit Modules and Testbench)

##### A. 二元減法器之設計 (Design of Binary Subtractor)

- (a) **半減器(Half Subtractor)**：設計一個半減器(half subtractor, HS)，有兩個輸入變數及兩個輸出變數。輸入變數為被減數  $x$  與減數  $y$ ；輸出變數為差值  $D$  與借位輸出  $B$ 。

Design a half subtractor (HS) which has 2 input variables and 2 output variables. The input variables are the minuend (被減數)  $x$  and the subtrahend (減數)  $y$ , and the output variables produce the difference  $D$  and the borrow-out  $B$ .

- i. 請以 gate-level modeling 方式撰寫其 HDL 電路模組，模組名稱與 port list 請訂為 **Lab2\_half\_sub\_gate\_level(output D, B, input x, y)**，檔案則命名為 **Lab2\_half\_sub\_gate\_level.v**。

Please write the Verilog circuit module in gate-level modeling. The circuit module and port list should be named as **Lab2\_half\_sub\_gate\_level(output D, B, input x, y)**, and its file should be named as **Lab2\_half\_sub\_gate\_level.v**.

- ii. 請以 dataflow modeling 方式撰寫其 HDL 電路模組，模組名稱與 port list 請訂為 **Lab2\_half\_sub\_dataflow(output D, B, input x, y)**，檔案則命名為 **Lab2\_half\_sub\_dataflow.v**。

Please write the Verilog circuit module in dataflow modeling. The circuit module and port list should be named as **Lab2\_half\_sub\_dataflow(output D, B, input x, y)**, and its file should be named as **Lab2\_half\_sub\_dataflow.v**.

- iii. 請以 behavior modeling 方式撰寫其 HDL 電路模組，模組名稱與 port list 請訂為 **Lab2\_half\_sub\_behavior(output D, B, input x, y)**，檔案則命名為 **Lab2\_half\_sub\_behavior.v**。

Please write the Verilog circuit module in behavior modeling. The circuit module and port list should be named as **Lab2\_half\_sub\_behavior(output D, B, input x, y)**, and its file should be named as **Lab2\_half\_sub\_behavior.v**.

- iv. 請撰寫一測試模組來測試上述三個以不同方式撰寫之半減器電路模組，請將此測試模組命名為 **t\_Lab2\_half\_sub**，檔案則命名為 **t\_Lab2\_half\_sub.v**

Please write a testbench to test the half-subtractor circuit modules which are described in three different ways above. The testbench module should be named as **t\_Lab2\_half\_sub**, and its file should be named as **t\_Lab2\_half\_sub.v**.

- (b) **全減器 ( Full Subtractor )**：設計一個全減器(full subtractor, FS)，有三個輸入變數及兩個輸出變數。輸入變數為被減數  $x$ 、減數  $y$ 、及借位輸入  $z$ ；輸出變數為差值  $D$  與借位輸出  $B$ 。

Design a full subtractor (FS) which has 3 input variables and 2 output variables. The input variables are the minuend (被減數)  $x$ , the subtrahend (減數)  $y$ , and the borrow-in  $z$ , and the output variables produce the difference  $D$  and the borrow-out  $B$ .

- i. 請利用(a)中的 gate-level 半減器來建構全減器。請撰寫出全減器之 HDL 電路模組，模組名稱與 port list 請訂為 **Lab2\_full\_sub(output D, B, input x, y, z)**，檔案則命名為 **Lab2\_full\_sub.v**。

Please use the gate-level half-subtractor designed in (a) to construct the full-subtractor. Please write the HDL circuit module of the full-subtractor. The circuit module and port list should be named as **Lab2\_full\_sub(output D, B, input x, y, z)**, and its file should be named as **Lab2\_full\_sub.v**.

- ii. 請撰寫全減器之測試模組，命名為 **t\_Lab2\_full\_sub**，檔案則命名為 **t\_Lab2\_full\_sub.v**。

Please write the testbench of the full-subtractor. The testbench module should be named as **t\_Lab2\_full\_sub**, and its file should be named as **t\_Lab2\_full\_sub.v**.

- (c) **四位元漣波借位減法器(4-bit Ripple Borrow Subtractor, RBS)**：設計一個四位元漣波借位減法器，以產生兩個四位元二進位數字相減之結果。其輸入變數為四位元二進位被減數  $X$ 、四位元二進位減數  $Y$ 、及借位輸入  $Bin$ ，輸出變數為四位元二進位差值  $Diff$  與借位輸出  $Bout$ 。

Design a 4-bit binary subtractor which may produce the arithmetic difference of two 4-bit binary numbers. The input variables are the 4-bit binary minuend (被減數)  $X$ , the 4-bit subtrahend (減數)  $Y$ , and the borrow-in  $Bin$ , and the output variables produce the 4-bit difference  $Diff$  and the borrow-out  $Bout$ .

- i. 利用**(b)**中之全減器來建構此 4-bit Ripple Borrow Subtractor (RBS)。請撰寫出此 RBS 之 HDL 電路模組，模組名稱與 port list 請訂為 **Lab2\_ripple\_borrow\_4\_bit\_sub** (output [3:0] **Diff**, output **Bout**, input [3:0] **X**, **Y**, input **Bin**)，檔案命名為 **Lab2\_ripple\_borrow\_4\_bit\_sub.v**。

Please use the full subtractor designed in **(b)** to construct the 4-bit Ripple Borrow Subtractor (RBS). Please write the HDL circuit module of the RBS. The circuit module and port list should be named as **Lab2\_ripple\_borrow\_4\_bit\_sub** (output [3:0] **Diff**, output **Bout**, input [3:0] **X**, **Y**, input **Bin**), and its file should be named as **Lab2\_ripple\_borrow\_4\_bit\_sub.v**.

- ii. 請撰寫此 RBS 之測試模組，至少以下述六組測試資料測試之。請將此測試模組命名為 **t\_Lab2\_4\_bit\_sub**，檔案則命名為 **t\_Lab2\_4\_bit\_sub.v**。

Please write the testbench of the RBS in which at least six test data showed in the following figure should be included. The testbench module should be named as **t\_Lab2\_4\_bit\_sub**, and its file should be named as **t\_Lab2\_4\_bit\_sub.v**.

X	Y	Bin
1101	0101	0
1100	1000	1
0101	1101	0
1000	1100	1
0101	0101	0
1011	1011	1

- (d) 四位元前看借位減法器(4-bit Borrow Lookahead Subtractor, BLS)：**設計一個四位元前看借位減法器，以產生兩個四位元二進位數字相減之結果。其輸入變數為四位元二進位被減數 **X**、四位元二進位減數 **Y**、及借位輸入 **Bin**，輸出變數為四位元二進位差值 **Diff** 與借位輸出 **Bout**。(Hint: 作法可參考課堂練習題說明。)

Design a **4-bit Borrow Lookahead Subtractor**, which may produce the arithmetic difference of two 4-bit binary numbers. The input variables are the 4-bit binary minuend (被減數) **X**, the 4-bit subtrahend (減數) **Y**, and the borrow-in **Bin**, and the output variables produce the 4-bit difference **Diff** and the borrow-out **Bout**. (Hint: Refer to the description in the class exercise.)

- i. 請撰寫出此 BLS 之 HDL 電路模組，模組名稱與 port list 請訂為 **Lab2\_borrow\_lookahead\_sub** (output [3:0] **Diff**, output **Bout**, input [3:0] **X**, **Y**, input **Bin**)，檔案則命名為 **Lab2\_borrow\_lookahead\_4\_bit\_sub.v**。

Please write the HDL circuit module of the BLS. The circuit module and port list should be named as **Lab2\_borrow\_lookahead\_sub** (output [3:0] **Diff**, output **Bout**, input [3:0] **X**, **Y**, input **Bin**), and its file should be named as **Lab2\_borrow\_lookahead\_4\_bit\_sub.v**.

- ii. 請以 2A(c) ii 所撰寫之測試模組(**t\_Lab2\_4\_bit\_sub**)測試此 BLS。

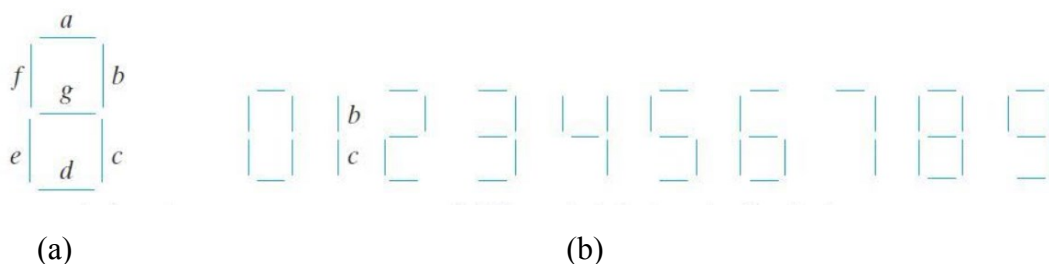
Simulate this 4-bit BLS by the same testbench of 2A(c) ii (**t\_Lab2\_4\_bit\_sub**).

## B. 二元碼十進制轉七段顯示解碼器之設計 (Design of a BCD-to-seven-segment decoder)

設計一個二元碼十進制(Binary coded decimal, BCD)轉七段顯示(seven segment

display)之解碼器。此電路為組合電路，其功能為將 BCD 編碼表示的十進位數值轉換為相對應的 7 段顯示器上的訊號。此電路有四個代表 BCD 編碼的輸入，以及七個代表七段顯示的輸出。輸入資料變數名稱為  $D$ ，有四個位元；資料輸出變數名稱為  $A$ ，有七個位元，分別表示七段顯示器中  $a$ 、 $b$ 、 $c$ 、 $d$ 、 $e$ 、 $f$ 、 $g$  等相對應的段點，如圖一(a)所示，以顯示出十進位數值的圖形，如圖一(b)所示。如果  $D$  的輸入不符合 BCD 的表示法時，則將  $A$  輸出全部設定為空白。此二進碼十進制轉七段顯示器解碼器之真值表如表一所示。

Design a BCD-to-seven-segment decoder. This decoder is a combinational circuit that converts a decimal digit in BCD to an appropriate code for the selection of segments in a display indicator used for displaying the decimal digit in a familiar form. The 4-bit input  $D$  of the decoder represents a decimal digit in BCD, and the seven-bit output  $A$  select the corresponding segments ( $a$ ,  $b$ ,  $c$ ,  $d$ ,  $e$ ,  $f$ ,  $g$ ) in the display as shown in Figure 1(a). The numeric display chosen to represent the decimal digit is shown in Figure 1(b). Design the BCD-to-seven-segment decoder using a minimum number of gates. The six invalid combinations should result in a blank display. The truth table of this decoder is given in Table 1.



圖一：(a)七段顯示器段點命名 (b)顯示各數字之段點圖形

Figure 1: (a) Segment designation (b) Numerical designation for display

表一：二進碼十進制轉七段顯示器解碼器之真值表

Inputs (BCD digit)				Outputs (7 segments)						
D[3]	D[2]	D[1]	D[0]	A[6]	A[5]	A[4]	A[3]	A[2]	A[1]	A[0]
				$g$	$f$	$e$	$d$	$c$	$b$	$a$
0	0	0	0	0	1	1	1	1	1	1
0	0	0	1	0	0	0	0	1	1	0
0	0	1	0	1	0	1	1	0	1	1
0	0	1	1	1	0	0	1	1	1	1
0	1	0	0	1	1	0	0	1	1	0
0	1	0	1	1	1	0	1	1	0	1
0	1	1	0	1	1	1	1	1	0	1
0	1	1	1	0	0	0	0	1	1	1
1	0	0	0	1	1	1	1	1	1	1
1	0	0	1	1	1	0	1	1	1	1
1	0	1	X	0	0	0	0	0	0	0
1	1	X	X	0	0	0	0	0	0	0

- i. 請以 gate-level modeling 方式撰寫其 Verilog 電路模組，模組名稱與 port list 請訂為 **Lab2\_BCD\_7segment\_decoder\_gatelevel** (output [6:0] A, input [3:0] D)，檔案則命名為 **Lab2\_BCD\_7segment\_decoder\_gatelevel.v**。  
Please write the Verilog circuit module in gate-level modeling. The circuit module and port list should be named as **Lab2\_BCD\_7segment\_decoder\_gatelevel** (output [6:0] A, input [3:0] D), and its file should be named as **Lab2\_BCD\_7segment\_decoder\_gatelevel.v**.
- ii. 請以 dataflow modeling 方式撰寫其 Verilog 電路模組，模組名稱與 port list 請訂為 **Lab2\_BCD\_7segment\_decoder\_dataflow** (output [6:0] A, input [3:0] D)，檔案則命名為 **Lab2\_BCD\_7segment\_decoder\_dataflow.v**。  
Please write the Verilog circuit module in dataflow modeling. The circuit module and port list should be named as **Lab2\_BCD\_7segment\_decoder\_dataflow** (output [6:0] A, input [3:0] D), and its file should be named as **Lab2\_BCD\_7segment\_decoder\_dataflow.v**.
- iii. 請以 behavior modeling 方式撰寫其 Verilog 電路模組，模組名稱與 port list 請訂為 **Lab2\_BCD\_7segment\_decoder\_behavior** (output [6:0] A, input [3:0] D)，檔案則命名為 **Lab2\_BCD\_7segment\_decoder\_behavior.v**。  
Please write the Verilog circuit module in behavior modeling. The circuit module and port list should be named as **Lab2\_BCD\_7segment\_decoder\_behavior** (output [6:0] A, input [3:0] D), and its file should be named as **Lab2\_BCD\_7segment\_decoder\_behavior.v**.
- iv. 請撰寫一測試模組來**完整測試**上述三個以不同方式撰寫之二元碼十進制轉七段顯示解碼器電路模組，請將此測試模組命名為 **t\_Lab2\_BCD\_7segment\_decoder**，檔案則命名為 **t\_Lab2\_BCD\_7segment\_decoder.v**。  
Please write a testbench to **completely test** the three different BCD-to-7-segment decoder circuit modules described above. The testbench module should be named as **t\_Lab2\_BCD\_7segment\_decoder**, and its file should be named as **t\_Lab2\_BCD\_7segment\_decoder.v**.

### C. 注意事項 : (Notes)

- 請用 ModelSim Student Edition 10.4a 做為開發環境。  
Develop your lab in ModelSim Student Edition 10.4.a.
- 請務必依照上述各項目之規定命名模組及檔案。  
Be sure to name the modules and files as described above.
- 禁止抄襲，違者(抄襲者與被抄襲者)以 0 分計算。  
Any assignment work by fraud will get a zero point.
- 助教會使用不同的測試模組來驗證同學的電路模組正確性。  
After you hand in your code, TA will use similar TestBench modules with different test data to verify the correctness of your design of the Verilog circuit modules.



### 3. 作業及 HDL 模組繳交(Hand in)

#### A. 作業報告繳交：word 檔，命名為 **Lab2\_學號\_姓名**

包含下列項目：配分含隱藏測資之測試及 Demo 狀況

- (1) 詳述半減器之電路設計流程，包括：真值表、布林代數式、邏輯電路圖。附上 2A(a)iv (半減器) 之模擬結果波形圖，並說明三個以不同方式撰寫之半減器電路模組之波形圖是否有差異及是否正確。(15%)
- (2) 詳述如何以半減器建構全減器，畫出電路方塊圖。附上 2A(b)ii (全減器) 之模擬結果波形圖，並說明是否正確。(10%)
- (3) 詳述如何以全減器建構四位元漣波借位減法器，畫出電路方塊圖。附上 2A(c)ii (4-bit RBS) 之模擬結果波形圖，並說明是否正確。(10%)
- (4) 詳述四位元前看借位減法器之電路設計流程，如：列出相關布林代數式(如： $P_i$ 、 $G_i$ 、 $B_i$ 、 $D_i$  等)。附上 2A(d)ii (4-bit BLS) 之模擬結果波形圖，並說明是否正確。(20%)
- (5) 詳述二元碼十進制轉七段顯示解碼器之電路設計，根據真值表推導出各輸出的最簡積之和(sum-of-product, SoP)式，並畫出電路邏輯圖。此外，請附上 2B. iv (二進碼十進制轉七段顯示解碼器) 之模擬結果，並說明是否正確。(35%)
- (6) 心得與感想、及遭遇到的問題或困難 (10%)

**Hand in a word file, named **Lab2\_StudentID\_Name** , including the following items:**

(Scores include answering problems in demo and the testing of extra data.)

- (1) Describe the design process of the half subtractor, including the truth table, the derived Boolean expressions, and the logic diagram. Attach the waveforms of the simulation results for the three modules of the half subtractor tested in 2A(a)iv, and determine whether the waveforms are correct or not and explain the difference of the waveforms, if any. (15%)
- (2) Describe how do you construct the full subtractor by using half subtractors as basic blocks and draw the block diagram of the circuit. Attach the waveform of the simulation results for the module of the full subtractor tested in 2A(b)ii, and explain whether it is correct or not. (10%)
- (3) Describe how do you construct the 4-bit ripple-borrow subtractor by using full subtractors as basic blocks and draw the block diagram of the circuit. Attach the waveform of the simulation results for the module of the 4-bit RBS tested in 2A(c)ii, and explain whether it is correct or not. (10%)
- (4) Describe the design process of the 4-bit borrow lookahead subtractor (BLS), for examples, deriving the Boolean expressions of  $P_i$ ,  $G_i$ ,  $B_i$ , and Diff. Attach the waveform of the simulation results for the module of the 4-bit BLS tested in 2A(d)ii, and explain whether it is correct or not. (20%)
- (5) Describe the design process of the BCD-to-seven-segment decoder in 2B. According to the truth table, derive the simplified sum-of-product expression for each output and draw the block diagram of the circuit. Moreover, attach the simulation results of the BCD-to-seven-segment decoder tested in 2B. iv, and explain whether it is correct or not. (35%)
- (6) Describe what you have learned from this lab unit and discuss the problems or difficulties encountered in this lab. (10%)

## B. Verilog modules 檔案繳交：13 files

Hand in the following Verilog modules: 13 files

Lab2\_half\_sub\_gate\_level.v、Lab2\_half\_sub\_dataflow.v、  
Lab2\_half\_sub\_behavior.v、t\_Lab2\_half\_sub.v、  
Lab2\_full\_sub.v、t\_Lab2\_full\_sub.v、  
Lab2\_ripple\_borrow\_4\_bit\_sub.v、  
Lab2\_borrow\_lookahead\_4\_bit\_sub.v、  
t\_Lab2\_4\_bit\_sub.v、  
Lab2\_BCD\_7segment\_decoder\_gatelevel.v、  
Lab2\_BCD\_7segment\_decoder\_dataflow.v、  
Lab2\_BCD\_7segment\_decoder\_behavior.v、t\_Lab2\_decoder\_4bit.v

## 4. DEADLINE

- 本實驗單元為一人一組，作業請上傳至 E3 平台。

This lab unit is **one student per group**. Please upload your Lab Report (word file) and the corresponding HDL code (.v files) onto e-Campus platform.

- 請將上述作業報告及 Verilog 電路模組與測試模組檔案(.v)全部壓縮成一個 **zip 檔** 或是 **rar 檔**(禁止上傳其他檔案格式)，並以「Lab2\_學號\_姓名」的方式命名，如：「Lab2\_0416000\_王大明」。

Please compress the word file of lab report and the Verilog circuit modules and testbench described above all into one **zip** file or **rar** file (other format is not accepted), and name the zip file as “**Lab2\_StudentID\_Name**”, for example, “Lab2\_0416000\_Kent Chang”.

- 作業繳交截止日期為 **2019/5/20 (一) 23:55**，不接受逾期繳交。

The **deadline for handing in lab report and Verilog files** is **May 20 (Monday) 23:55**. **No late hand-in is allowed.**

- **Demo** 時間暫定為 **5/22 (三) 1:00pm~9:30pm**，之後會再發公告通知大家上網填寫 Demo 時間表。未繳交作業者，將無法參加 Demo；雖有繳交作業但未 Demo 者，亦不予計分。

The **demo time** is arranged at **2019/5/22 (Wednesday) 1:00PM~9:30PM** tentatively, and we will send an announcement to inform you to fill the Demo schedule online. **Those who have not hand-in their lab reports and Verilog files will not be able to demo their work, and those who have not demo their lab units will get zero score.**

- 程式碼請勿抄襲別人或讓別人抄襲，經查證後此次 lab 總分一律以 0 分計算。

**Any assignment work by fraud will get a zero point**