
In-Circuit Serial Programming Guide

Microcontrollers are special embedded processors that are capable of executing specific code with a high efficiency. They are used throughout the world in various devices ranging from handheld gaming devices, medical units, military hardware, and digital signage. Recently, the Arduino foundation made playing with microcontrollers easier as they created a platform where users could write code, plug in a microcontroller over USB, flash the chip, and see the results - nearly in real-time. They helped usher in the Maker Renaissance we found ourselves in today, by obfuscating the more complex tasks in microcontroller programming using high-level software and other microcontrollers.

The purpose of this guide is to help de-obfuscate low-level microcontroller programming by showing you what is really happening when you give the "Upload" command in the Arduino IDE.

What is In-Circuit Serial Programming?

In-Circuit Serial Programming (ICSP) is the fundamental way to program a microcontroller. Microcontrollers typically store their programs on SPI flash memory which can be read or written over as the programmer demands. By temporarily disabling the microcontroller and overwriting the contents of the SPI flash memory, we can reprogram the microcontroller with different code.

On the Arduino boards, when you upload code over USB, a secondary microcontroller on the board interprets the USB communications and translates them to the UART serial protocol. The bootloader on the main microcontroller then uses the data coming from the UART bus to reprogram the SPI flash memory, thus reprogramming the Arduino. This is a form of ICSP, but adds complexity to both the circuit and fundamental microcontroller firmware.

A simpler version of ICSP is accessing the SPI flash memory directly. On the Arduino Uno board, the ICSP header is easily visible and can be used by any device that has an SPI bus to reprogram the microcontroller. If, for instance, the USB-Serial bridge on the board has its program memory corrupted ICSP can be used to re-flash the correct firmware onto the chip. Alternatively, if the chip is completely non-functional, the primary microcontroller can still be used with new code being deployed over the ICSP pins.

Note that different microcontrollers may have different implementations of ICSP. Another popular form is the Single Wire interface. Please refer to your microcontroller's datasheet for specific information.

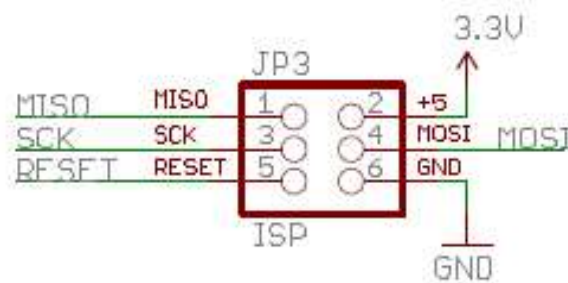


Figure B.1: Pinout of the Arduino Uno and Mega ICSP header

Arduino as In-circuit Serial Programmer

For this example, we will be using an Arduino as an In-circuit Serial Programmer (ISP) to program another Arduino over ICSP. The Arduino Foundation provides a sketch in the examples folder of the Arduino IDE to configure an Arduino board as an ISP. First, plug in the Arduino Uno to the ICSP header as shown in Figure B.2 and according to Table B.1. On most boards, there is no reverse-polarity protection, so make sure the 5V and GND wires are plugged in correctly.

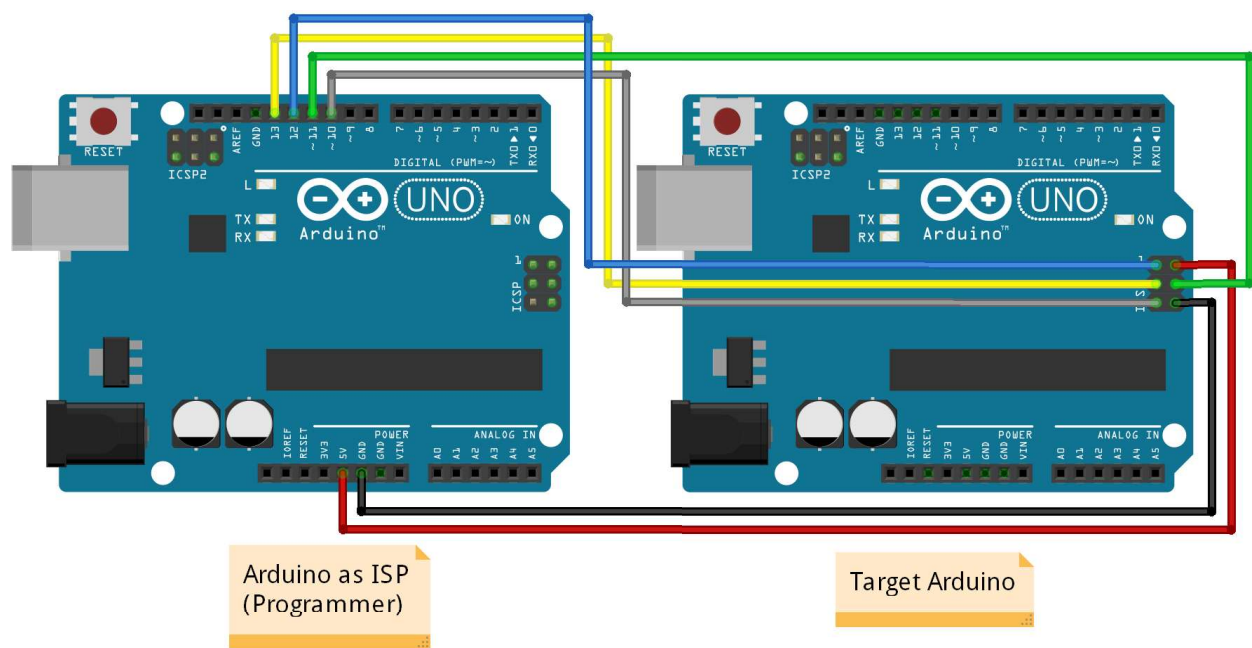
Table B.1: ArduinoISP hookup table for target and programmer

Programmer	Target
DIO 12	MISO (Pin 1)
DIO 13	SCK (Pin 2)
DIO 10	RESET (Pin 3)
5V	5V (Pin 4)
DIO 11	MOSI (Pin 5)
GND	GND (Pin 6)

After wiring up the boards, plug the Arduino Uno into the programming computer. This will apply power to the system and should allow you to program the Uno as you normally would. Then, navigate the ArduinoISP sketch located in the “examples” folder of the Arduino IDE (Figure B.3) and upload the sketch to the Arduino Uno.

Once the ArduinoISP sketch is uploaded, navigate to a sketch to upload to the target board configuring the compiler to the target board and processor (Figure B.4). Use the same COM port as the Arduino Uno and use the “Upload Using Programmer” option shown in Figure B.5. If you get any errors such as “Unable to communicate with device” or “Invalid device signature”, check your wiring and try again.

While this example used the basic Blink example code, this process can be done for any appropriate Arduino sketch onto most Arduino-compatible boards. On some embedded devices, a common USB interface may not be accessible and therefore ICSP is the only programming option.



fritzing

Figure B.2: Diagram showing how to hook up an ArduinoISP programmer and Arduino ICSP target. Retrieved from <https://learn.sparkfun.com/tutorials/installing-an-arduino-bootloader/hardware-hookup>

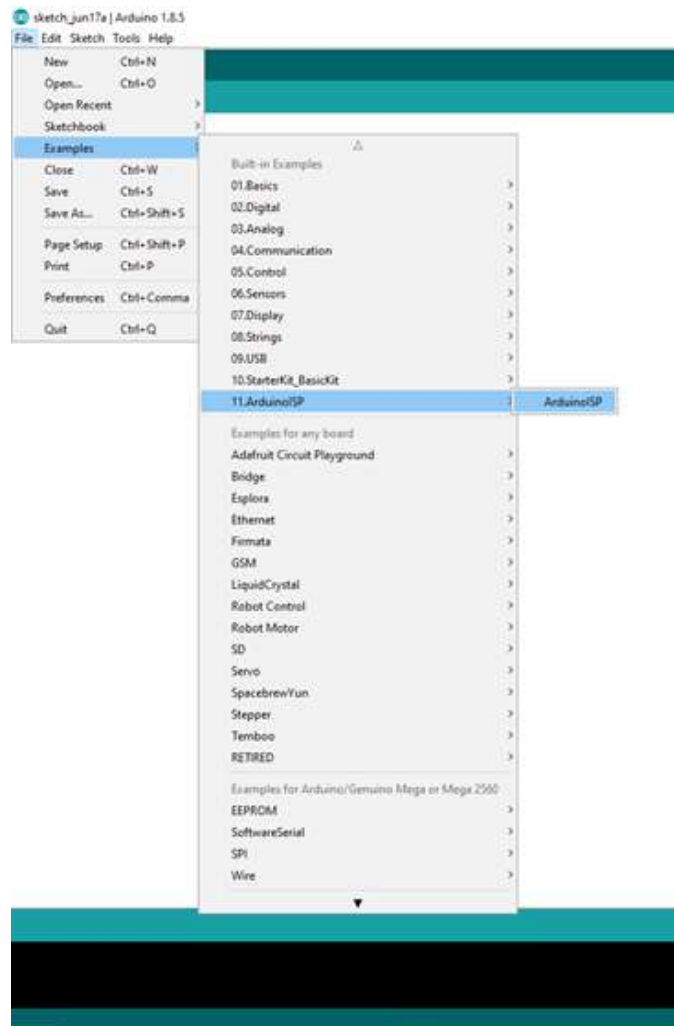


Figure B.3: Location of ArduinoISP sketch in the Arduino IDE

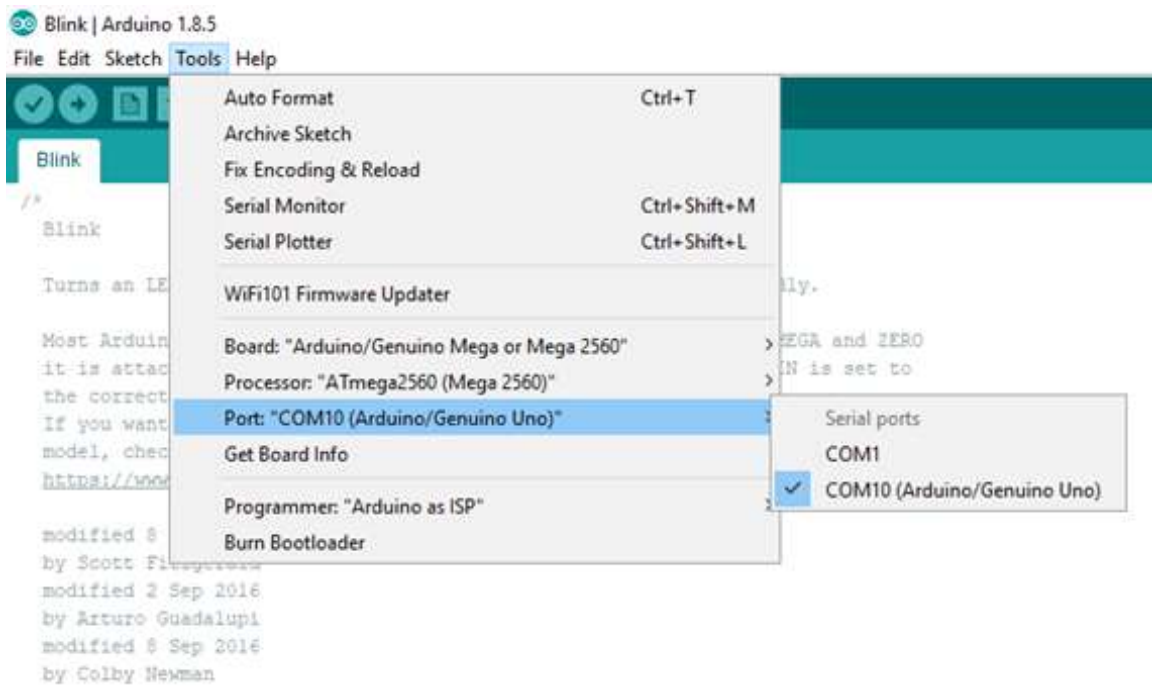


Figure B.4: Configuring the Arduino IDE to compile for the correct board

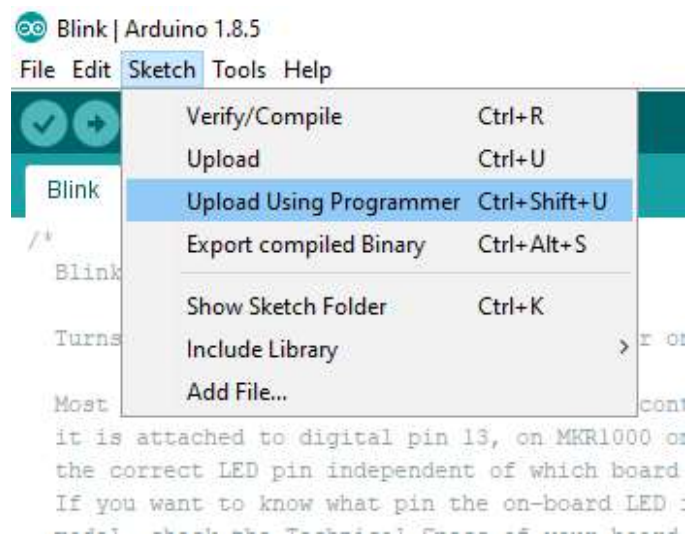


Figure B.5: Upload Using Programmer sketch option

Using a Raspberry Pi as ISP

For the graduate portion of this class, we will be using a Raspberry Pi to upload code to the Arduino boards over ICSP. The Raspberry Pi uses 3.3V logic levels which are not completely compatible with the 5V logic levels of the Arduino board. Therefore, it is strongly recommended to use a breadboard to breakout the Raspberry Pi's pins to a logic level converter and connect it from there to the Arduino's ICSP header. Please refer to Figure B.6 for hookup information. The pinout for this configuration can be found in the figure, which we will use later with AVRDUDE

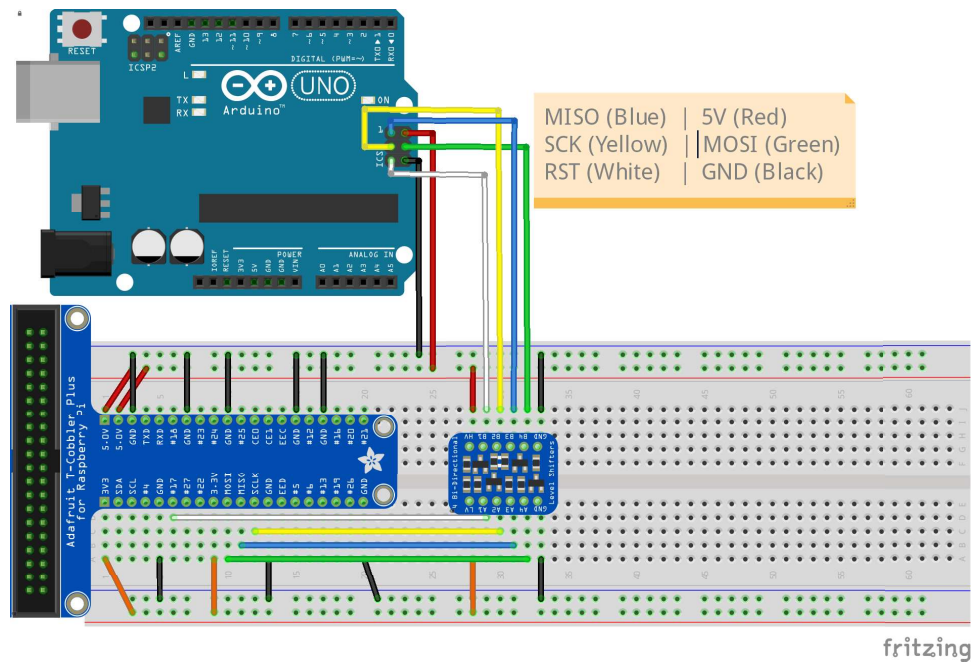


Figure B.6: A wiring diagram of how the Raspberry Pi should be connected to the Arduino ICSP headers through a breadboard and a logic-level converter. Created using Fritzing <https://fritzing.org>

Table B.2: Raspberry Pi as ISP hookup table for target and programmer

Programmer	Logic Level Converter	Target
3V3	LV	NC ¹
NC ¹	HV	5V
GPIO 17	A1/B1	RESET
GPIO 11 (SCLK)	A2/B2	SCK
GPIO 9 (MISO)	A3/B3	MISO
GPIO 10 (MOSI)	A4/B4	MOSI
GND	GND	GND

Setting up AVRDUDE

AVRDUDE is the software package that will upload machine binary to the microcontroller's program storage. The following steps will assume you have already set up the Raspberry Pi with RaspberryPiOS and updated

¹ Not connected

the latest packages. Through this example, we will be operating inside a command terminal through a remote secure login shell, but this process can be repeated inside the command terminal of a headed set up.

First, in the open terminal execute the following command:

```
sudo apt-get install avrdude
```

This will install AVRDUDE on the Raspberry Pi so we can flash .hex files onto the microcontroller. To verify the installation, execute:

```
avrdude -v
```

If the output is something like:

```
avrdude: Version 6.3-20171130
  Copyright (c) 2000-2005 Brian Dean, http://www.bdmicro.com/
  Copyright (c) 2007-2014 Joerg Wunsch

  System wide configuration file is "/etc/avrdude.conf"
  User configuration file is "/home/pi/.avrduderc"
  User configuration file does not exist or is not a regular file, skipping

avrdude: no programmer has been specified on the command line or the config file
  Specify a programmer using the -c option and try again
```

Then the installation is good and AVRDUDE has created a user configuration file that we can edit. To begin this process, execute the following commands in the terminal:

```
cp /etc/avrdude.conf ~/avrdude_gpio.conf
```

```
nano ~/avrdude_gpio.conf
```

The first command copies the default AVRDUDE configuration file to a new file in the home directory of user. The second command will open this file in the Nano file editor, pulling up a screen like Figure B.7.

Once in the file, press CTRL__, then CTRLV to navigate to the bottom of the file. There, paste the following block of code:

```
programmer
  id = "gpio_icsp";
  desc = "Use the Linux sysfs interface to bitbang GPIO lines for programming the Arduino;
  type = "linuxgpio";
  reset = 17;
  sck = 11;
  mosi = 10;
  miso = 9;
;
```

This creates an AVRDUDE programmer that uses the GPIO pins specified in Table B.2 to program the Arduino over ICSP. Press CTRL+X then Y then ENTER to save and exit the file; the AVRDUDE programming tool is now configured.

```

pi@argo-controller: ~
GNU nano 2.7.4 File: /home/pi/avrdude_gpio.conf

$Id$ -*- text -*-
#
# AVRDUDE Configuration File
#
# This file contains configuration data used by AVRDUDE which describes
# the programming hardware pinouts and also provides part definitions.
# AVRDUDE's "-C" command line option specifies the location of the
# configuration file. The "-c" option names the programmer configuration
# which must match one of the entry's "id" parameter. The "-p" option
# identifies which part AVRDUDE is going to be programming and must match
# one of the parts' "id" parameter.
#
# DO NOT MODIFY THIS FILE. Modifications will be overwritten the next
# time a "make install" is run. For user-specific additions, use the
# "-C +filename" commandline option.
#
# Possible entry formats are:
#
# programmer

```

[Read 15870 lines]

^G Get Help ^O Write Out ^W Where Is ^K Cut Text ^J Justify ^C Cur Pos
^X Exit ^R Read File ^\ Replace ^U Uncut Text ^T To Spell ^_ Go To Line

Figure B.7: The top of the avrdude_gpio.conf file in Nano

Preparing a Sketch for ICSP Uploading (Arduino)

Once you have a sketch ready for the microcontroller to run, configure the compiler for your board, same as Figure B.4. Select the “Export compiled Binary” option in the Arduino IDE (Figure B.8). This will create two files in the sketch’s directory, both ending with “.hex”, but one will have “.with_bootloader” in the middle. The file we want to upload is the one without the bootloader, highlighted in Figure B.9.²

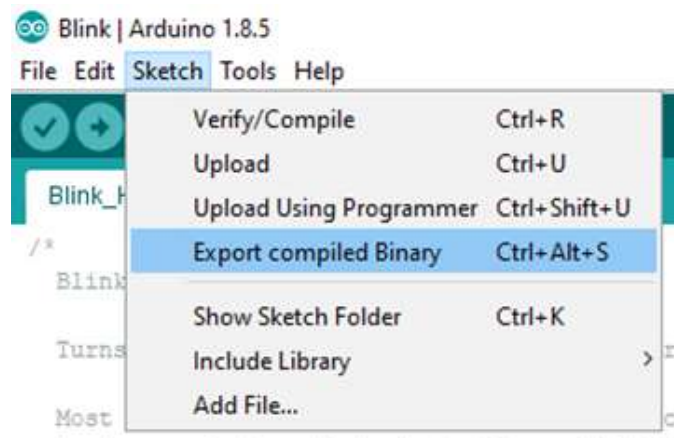


Figure B.8: Arduino IDE “Export compiled Binary” option

² This will disable the USB programming bootloader. This will need to be re-flashed with the bootloader if you want to upload code to the microcontroller via USB again.







Name	Status	Date modified	Type	Size
 Blink_Hex		06/17/2019 16:55	INO File	2 KB
 Blink_Hex.ino.mega.hex		06/17/2019 16:55	HEX File	5 KB
 Blink_Hex.ino.with_bootloader.mega.hex		06/17/2019 16:55	HEX File	24 KB

Figure B.9: The sketch and its compiled binaries in their folder

Preparing a Sketch for ICSP Uploading (VS Code)

This part assumes you have already initialized the Arduino development environment within VS Code. In VS Code, open the “arduino.json” file in the /.vscode folder of your workspace. Add the following line to the bottom of the file:

```
"output": ".arduinobuild"
```

This will create a new folder in the root directory of the workspace called “.arduinobuild” that will hold all of pre-compiled binaries for your Arduino sketch, logs, and other things that are not important right now. Inside this folder will be two files: “[sketch_name].ino.bin” and “[sketch_name].bootloader.bin”. As before, the one we want to upload is the one without the bootloader.¹

Programming the Microcontroller

Transfer the binary file to the Raspberry Pi using your preferred method of choice. This is most easily done over a USB stick or a File Transfer Protocol like Secure Copy. Applications like WinSCP make this process easy for beginners. Place the file in a working destination directory - ideally, a project folder you have already set up beforehand. Then, open a terminal on the Raspberry Pi and execute the following command:

```
sudo avrdude -p [Microcontroller] -C ~/avrdude_gpio.conf -c gpio_icsp -v
```

Note: the [Microcontroller] in this command needs to be replaced with the name of the microcontroller in use (e.g. “atmega328p” for the Arduino Uno or “atmega2560” for the Arduino Mega).

This will verify that the Raspberry Pi can talk to the microcontroller and verifies that the chip is operating nominally.

If there are any issues, make sure you are executing this command with “sudo” and that the configuration file matches with the GPIO pins used in the schematic; check the wiring connections to the Arduino; and check that the file path for “avrdude_gpio.conf” is correct.³

Once you have established communications with the Arduino, execute:

```
sudo avrdude -p [Microcontroller] -C ~/avrdude_gpio.conf -c gpio_icsp -v -U flash:w:[filename]:i
```

Where again [Microcontroller] needs to be replaced with the name of the microcontroller and [filename] needs to be replaced with the path and name of the binary sketch file you copied to the Raspberry Pi. The end of a successful write should look something like this:

³ The “~” in the file path only denotes the relative directory you are currently in. If the file is NOT in the same directory that you are executing the command in, you must put the path in lieu of the “~”.

```

avrdude: AVR device initialized and ready to accept instructions

Reading | ##### | 100% 0.00s

avrdude: Device signature = 0x1e9801 (probably m2560)
avrdude: safemode: lfuse reads as FF
avrdude: safemode: hfuse reads as D8
avrdude: safemode: efuse reads as FD
avrdude: NOTE: "flash" memory has been specified, an erase cycle will be performed
        To disable this feature, specify the -D option.
avrdude: erasing chip
avrdude: reading input file "Blink_Hex.ino.mega.hex"
avrdude: writing flash (1462 bytes):

Writing | ##### | 100% 0.41s

avrdude: 1462 bytes of flash written
avrdude: verifying flash memory against Blink_Hex.ino.mega.hex:
avrdude: load data flash data from input file Blink_Hex.ino.mega.hex:
avrdude: input file Blink_Hex.ino.mega.hex contains 1462 bytes
avrdude: reading on-chip flash data:

Reading | ##### | 100% 0.82s

avrdude: verifying ...
avrdude: 1462 bytes of flash verified

avrdude: safemode: lfuse reads as FF
avrdude: safemode: hfuse reads as D8
avrdude: safemode: efuse reads as FD
avrdude: safemode: Fuses OK (E:FD, H:D8, L:FF)

avrdude done.  Thank you.

```

If there is an error (most commonly with a file name) it will likely occur after the first reading block. The `-v` argument of the command gives error statements in the output so you can error trace and find the problem.