# ELECTRONOTES

**APPLICATION NOTE NO. 380**

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## FUN WITH LIGHTING SWITCHES – SIMPLE BUT SOMETIMES FRUSTRATING

Recently ( See Webnote 5) I mentioned a problem with arcing in CFLs (Compact Florescent Lamps) which I thought wrecked the switches over time. I mentioned that I would have to change out two switches, and indeed, I did this and one was bad. As I guessed, these are hard to troubleshoot. Logically I knew which of the pair was bad – and the logic must have been wrong, as it was the other one. Actually, the logic was incomplete, as we shall see. This got me to thinking about switch wiring, a quotidian matter for sure in the life of an electrical engineer. So why is it so hard!

## BASICS

This actually was one of those cases where you have two switch locations controlling one light (or set of lights). For a reason I can't possibly understand, these are called "three-way" switches (perhaps because there are three terminals?). When they work, they are obviously very convenient. There are some minor drawbacks in applications, and in trouble shooting failing switches. **Back to the basics – One Switch**.

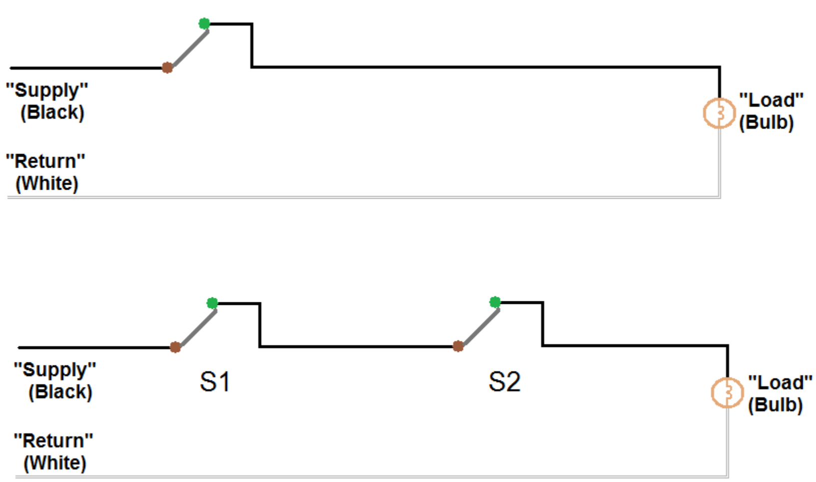



Fig. 1 The top shows a conventional one-switch single-pole single-throw (SPST) setup. Note that the switch closes or interrupts the black supply line. Two switches in series (bottom) will not guarantee a turn-on at either switch, but possibly offer a guaranteed emergency cut-off. This is seldom seen though.

With a single switch (Fig. 1, top) unless someone MOUNTS the switch upside down, ON is always UP (usually marked - at least in the US). Note that it is impossible to wire this two terminal switch wrong, but it is possible to MOUNT it wrong. It is usually a simple matter to correct this. You just take off the cover plate by removing two screws. Then remove the two screws that secure the actual switch, pull it out and give it a 180° twist, and reinstall. Don't change any wiring. That is, the fix is not electrical, but mechanical.

No one reading this would suppose they could use two "Single-Pole Single-Throw" (SPST) switches to control the one light, in the manner of putting two switches in series (Fig. 1, bottom), or in parallel (not illustrated). Indeed, you need a different kind of switch, and three-conductor cable. Now, let's be specific about the cable. Ordinary "two-conductor" wiring cable has two insulated conductors (white and black), and one bare conductor. Even though black is usually ground in our bench work, in house wiring, black is the "hot" or "supply" while white is the "return" (or is supposed to be).

Back at the breaker box (or fuse box) this return is connected to ground, as is the bare wire. Thus the white wire is usually an insulated version of the bare wire, and both are grounded. So you might suppose you can touch either one with abandon. Not so! The white wire, being insulated, is sometimes used for a different purpose than the one shown in the simple circuit of Fig. 1. In some setups, electrical code requires that when this is done, the white wire is "taped black" which means it has black electrical tape around the end. But don't be surprised if this has not been done.

An additional point before moving on to three conductor cable is that if the installation has a Ground Fault Interrupt (GFI), the current being supplied by the black wire needs to be matched (to a high precision - to about 5 ma) by the current actually going back through the white wire, as monitored at the GFI socket. So, if you were to suppose that you could just connect the return terminal to the bare ground wire, (perhaps the white wire is inconvenient) you will pop the GFI. So never assume that white is ground. Never ASSUME anything about high voltage and high current.

Further, the (bare) ground wires are supposed to be connected to the metal boxes the switch or lamp fixture is mounted in. In the case of a new switch, or a new socket, there is usually a particular terminal to which this is to be attached. This terminal in turn is connected to (is part of) the metal mount of the switch or socket, and then when the device is mounted and its screws tightened, the metal box is conveniently grounded (as will be the screws that hold the cover plate on). But, lamp fixtures often do not have any ground terminal, and switches, sockets, and lamps are often mounted in plastic rather than metal "workboxes". Accordingly grounding is often neglected, or discontinuous at some point. (I have seen wiring, done by a "professional" builder where the bare wires were left floating around inside the breaker box.) Trust nothing.

This is probably also a good point to mention the differences between drawing a workable circuit on paper, and actually installing the wiring. In Fig. 1 (top) we showed the switch as an interruption of the black wire passing through. That is, the current is on the way from the supply to the lamp, and passes through the switch box. Both switch terminals are connected to black wires. But what if the current goes to the lamp first (if it happens to be closest), and the switch is remote? Is it necessary to run two cables to the switch and use only black wires. Clearly we would just run a single cable to the switch, connecting the white and black wires to the two terminals. At the other end, the white and black wires are essentially remote extensions of these two switch terminals. The switch is then "available" back at the lamp mounting workbox. This is an example of a white wire that will be hot.

In general, on paper, wire routes and lengths are freely chosen. We just draw working circuitry. In practice, we usually need to conserve wire for cost reasons and to minimize resistance. Accordingly, you could well imagine running cables here and there and wire exactly what you want (what you drew). But a professional electrician has to treat different arrangements separately. For example, in a three-ways setup, there might be a switch inside a garage, a lamppost outside the garage, and a second switch out at the end of the driveway. Three-way switches are difficult enough, but the professional must consider quite different arrangements according to the physical positioning of the switches and the lamp fixture. You can find all this in books or on the internet. For the most part, these instructions are of the nature of "connect the red wire to terminal two…"). You don't find a wiring schematic I always wonder if the pros just know the connection list, of if they are thinking about the circuitry.

## THE THREE-WAY

Let's acknowledge that readers here are interested in circuits first, implementation second, and that the real understanding is in a circuit diagram, not a listing or interconnections. So we find that the three-way (two switches controlling one lamp) can be done as in Fig. 2. Here the two switches are not SPST, but Single-Pole Double-Throw (SPDT), and the cable used is three-conductor. This cable has three insulated conductors as well as the bare wire ground. The added wire is usually red, and it should always be assumed to be hot, or at least, unknown.


Fig. 2 Two switches (single-pole double-throw) controlling one light - the so-called "three way". Top: one of the two ON states - using the Red wire. By changing S2 (bottom), the light is OFF. Changing S1 will then turn the bulb back on using now the Black wire. And so on.

Whether or not an ON condition is achieved with an UP or a DOWN depends on the other switch position. It is obvious how this works. Only the black wire or the red wire is ever involved at any setting of the switches. Further, ON or OFF of any one switch is a matter of the history of use. Thus if you have two switches, but almost always use one, and it happens to have been left in the condition that ON is DOWN at your usual switch, you will be tempted to walk to the second switch and flip it so that the UP is ON for your preferred switch. More likely, you know that the light is ON because you see that it is lit, and you never even think of UP or DOWN anyway. But sometimes, that light is not visible (perhaps an outside fixture – and this is particularly hard to observe in daylight). But these are not very tough problems – when things are all working.

So, suppose you are installing a 3-way yourself. Does it matter which of the red or black wires is connected to the top or bottom terminals at either switch. Of course not (Fig. 3). Well, more on this later. But perhaps it does if you are an electrician. If you look at the instructions on the box (or on web pages) they will probably tell you to connect a certain colored wire to a certain screw. No such diagram as Fig. 2 is offered. (In fact, if you want to find the configuration of your switch, you may need your ohmmeter.) So it may "matter" because of a code requirement. You really need to consider this, and since it will "work" just as well wired to code as it does to your logical understanding, do it to code.

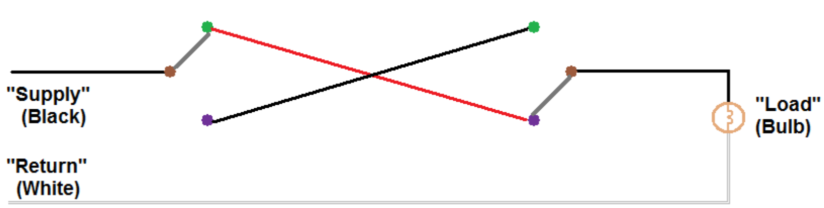
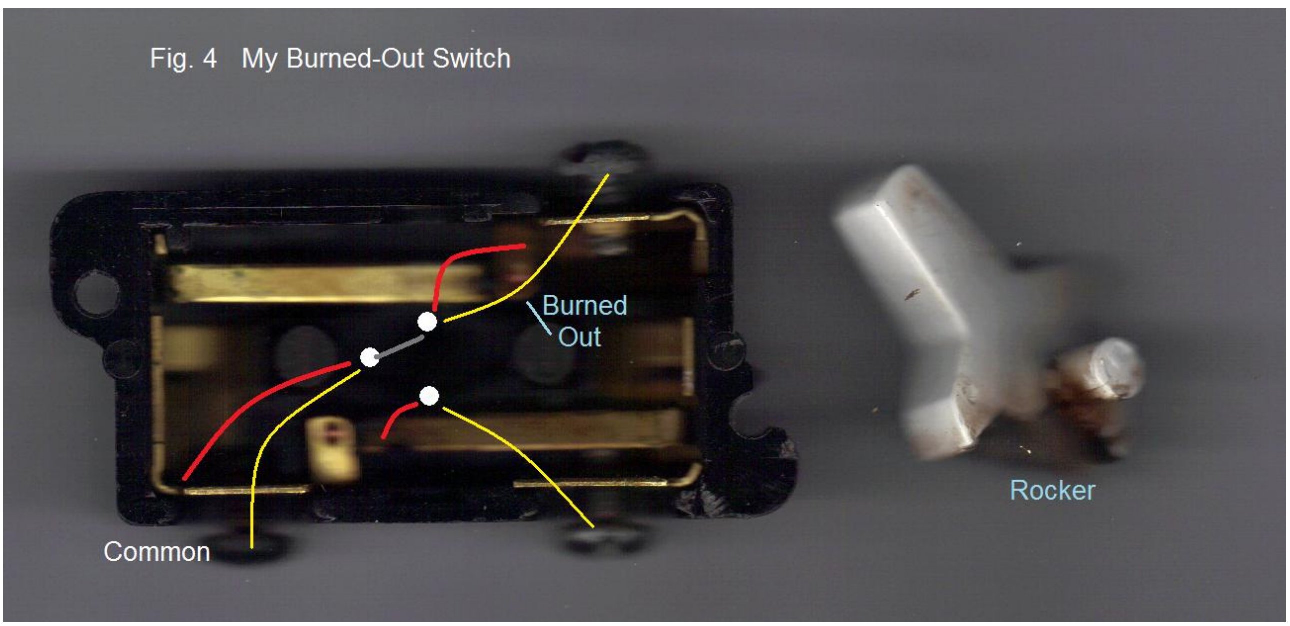



Fig. 3 Crossing over the Red and Black wires works just as well, but might be a violation of electrical code.

What can go wrong? Well note that, as in Fig. 1, Fig. 2 is just a more complicated way to complete or interrupt the black wire path between the supply and the fixture. Make some sketches. There is absolutely no way to connect the three wires (black incoming, red outgoing, and black outgoing) such that you will cause a short. Further, it is impossible to miss-wire one of the switches so that the light won't come ON for some combination of settings. (This is where the fun here is – making all the drawings).

To understand better why the wiring is not easy, Fig. 4 shows a scan of the bad switch I took out and took apart. The body of the switch is the brown plastic, the rocker (switch handle) pushes DOWN one of the horizontal brass strips, or the other, disconnecting it. By the springiness of the brass strips, both would be closed. With this switch, in fact, one of the terminals is labeled "common" (in small letters) on the back (the lower left one). Note that one of the brass strips (the upper one) is the same as the common, while the other brass strip (lower) is the same as the outer terminal (lower right). So there is a lack of symmetry that might confuse – but you aren't going to take apart the switch before using it anyway. The point is, that from just the screw terminals, it is not obvious which terminals are which. So it is entirely possible to mess UP connections.




If we mistake an outer terminal for the center, and we do it for both our switches, then the situations in Fig, 5, upper, results. One switch will turn the light ON and OFF, and the other will turn it ON and OFF only when the first is ON (same as two SPST switches in series). If the red and black wires cross over, we get Never ON (Fig. 5, lower).

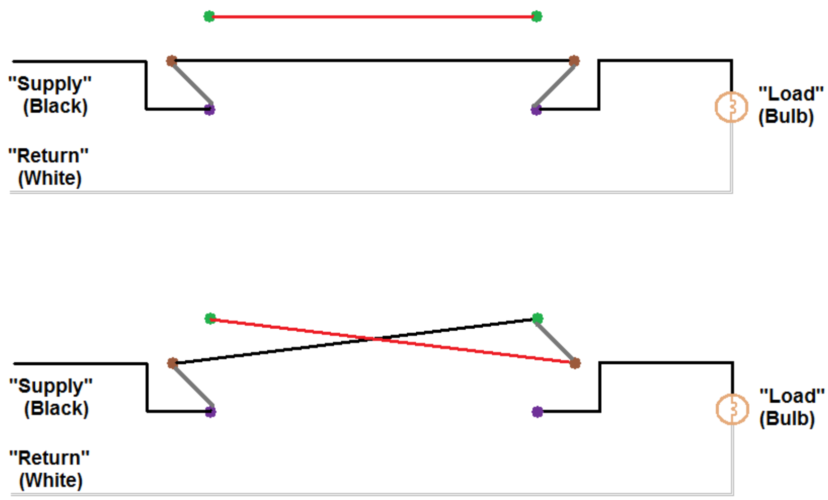



Fig. 5 A wiring error, for which the supply line is connected to an outside terminal rather than to the center terminal is equivalent to two switches in series (Top). If in this case, the Red and Black wires are also crossed over, we arrive at a never ON situation (Bottom).

Perhaps more commonly, we find that only one switch is miss-wired, particularly as you are replacing one you thought was bad. Fig. 6 shows such a case. As we shall see, there are plenty of other cases that will perform exactly the same as this error does.

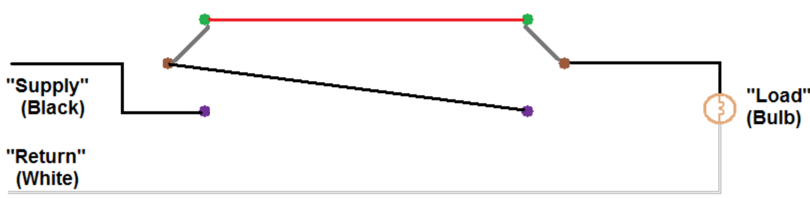



Fig. 6 One of the switches (right side) is wired wrong. Equivalent to two SPST switches in series.

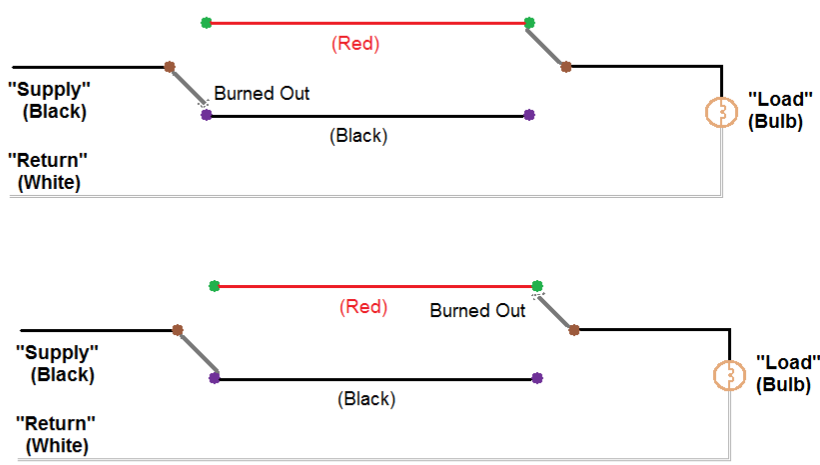
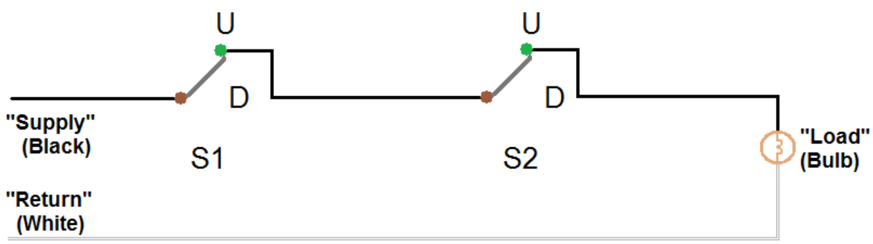



Fig. 7 Wired correctly but one set of contacts is burned out - left side in top figure, right side in bottom figure. Again looks like two SPST switches in series.

Fig. 7 shows two of four possible cases where a switch is “burned out”.  Here we really mean that one set of contacts (of the two) is not closing.  Perhaps the springiness of the strips is lost, or metal is burned away, or both.  The switch is thus defective, although one set of contacts is almost certainly still good.  This will mean that it is possible to light the lamp, but only the red wire or the black wire will be contacted from both sides.  This is equivalent to the two SPST switches in series (again, as in Fig. 1).

# TRUTH TABLES

Here we have two switches, each of which could be either UP or DOWN, so there are four possible combinations, and we could consider sketching the current flow for all four possible cases, making drawings such as the ones we have been doing here.  However, the reader has probably supposed that we can use a “Truth Table” approach here, a 2 x 2 grid for Switch S1 (U or D) and for Switch S2 (U or D) and in the grid, use some sort of symbol to indicate the light is ON, OFF, or should be ON but isn’t (OFF AB = abnormal).

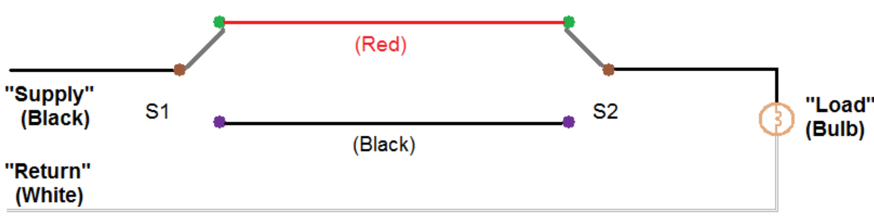



| S2 \ S1 | U | D |
|---|---|---|
| U | ON | OFF |
| D | OFF | OFF |

Fig. 8  Truth Table for Two SPST Switches in Series

The truth table for the two SPST switches, for example, is shown in Fig. 8.  Only one setting of the switches, both UP, results in the light coming ON. Thus the truth table has only one non-OFF entry.

The corresponding truth table for a three-way is shown in Fig. 9. Here we have the switch ON if both switches are UP, of if both are DOWN, otherwise, otherwise.  Here is the

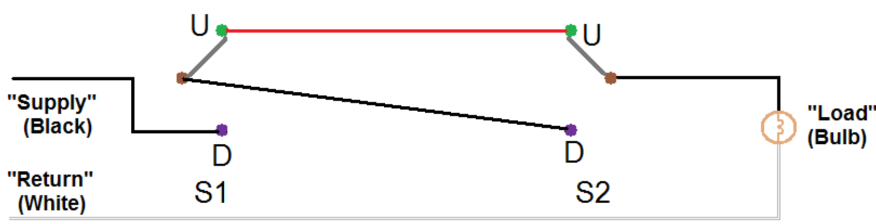



| S2 \ S1 | U | D |
|---|---|---|
| U | ON | OFF |
| D | OFF | ON |

Fig. 9   Truth Table for Three-Way

best place to mention that if the red and black wires are crossed over at one of the two switches (Fig. 3) the truth table will invert. Thus if you get up and go to your nearest three-way that is on, find the switch position as UP or DOWN, bet that the other switch should be the same – and go look. If not, someone crossed the wires over, and that's not unusual. However, I would also bet that it never occurred to you, or was your observation, that the switches should be symmetrical. You just toggle the switch that is not doing what you want (turning ON or OFF) and that's all there is to it. You don't expect UP or DOWN to mean anything.

Fig. 10 shows the case of the wiring error, and the truth table is that of the two SPST switches in series, except we have indicated, using "AB" that the OFF is abnormal. If at this point, you have just replaced a switch of a malfunctioning three-way and it still does not work, you are probably frustratingly, hopelessly lost!




| S2 \ S1 | U | D |
|---|---|---|
| U | OFF AB | OFF |
| D | OFF | ON |

Fig. 10 Truth Table for Wiring Error

Finally, and this is really the main point, because we are postulating that you had a three-way system that was working, and it is now malfunctioning. Almost certainly you can construct and observe a truth table (and do fill it in) that has only one ON entry. Does that tell you what is wrong? NO it does not.

Fig. 11 shows the four cases where one section of one switch has burned out. It would be extremely unusual to have two (or more) sections burned out at the same time. So there are four possibilities, as shown in Fig. 11. But there are only two unique truth tables. So we are up the creek. Further, note that each of the situations corresponding to either one of the two truth tables involves burn-outs in either side. So you really can't tell from performance which switch is bad. So even though my logic told me that it was a particular switch, if I had been more careful I would have seen that a burn-out in the opposite side of the other switch was also consistent with the evidence. This should not have been a surprise! We didn't really need the truth tables. If either wire, red or black, is not accessed due to a burn-out, on either side, that link will not work, and you can't tell which switch is bad. So this was a long way to the truth!

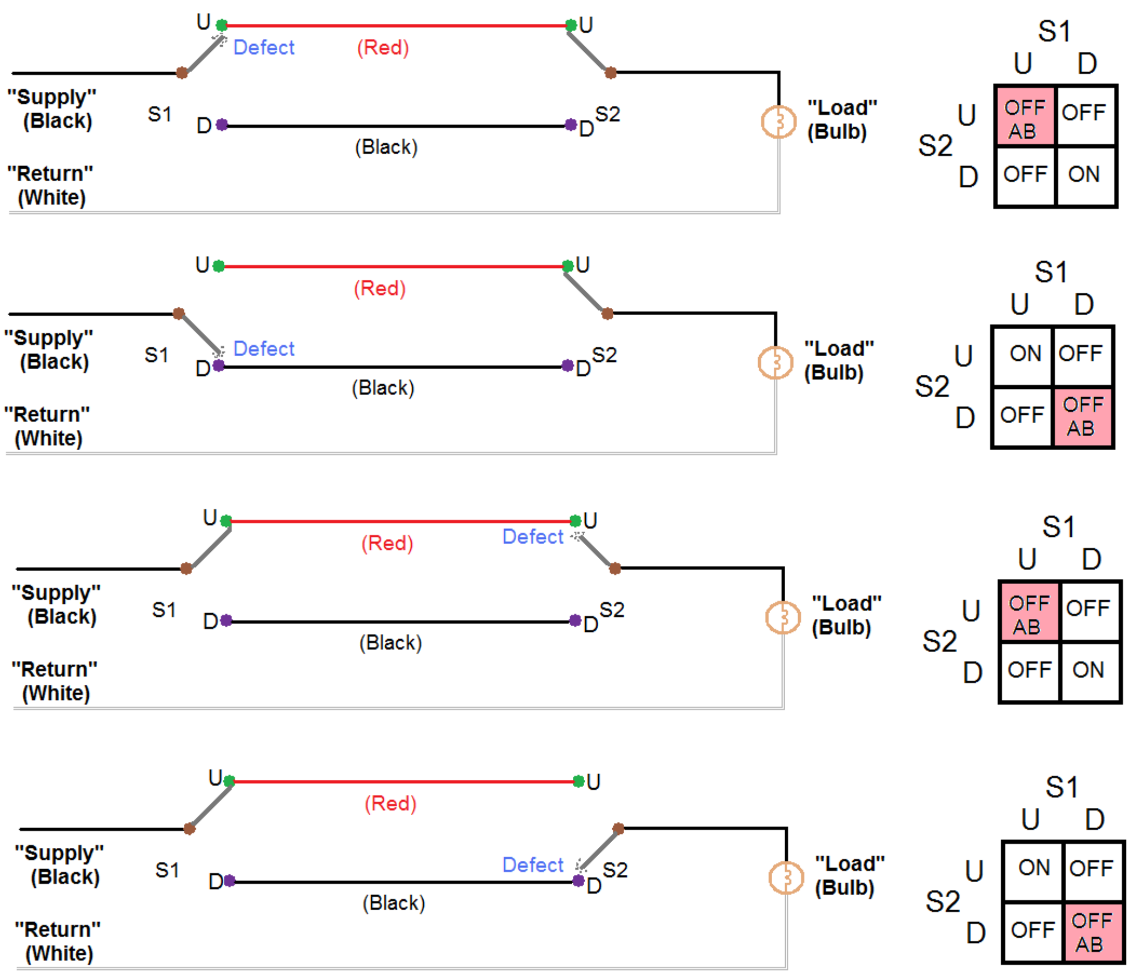



Fig. 11 Truth Tables for Defective Burn-Out

Well, perhaps not. Here is the situation. The circuit does not work so you go out and buy one switch. (Incidentally, I had in mind that these three-ways cost something like $5 while the regular SPST switches were well under $1. I found the three-ways for over $5 but also some for less than $2. So not so bad.) Since we now agree that you can't tell from the performance (truth table) which switch is bad, you need to remove one, <u>and test it with your ohmmeter after removing it – don't replace it yet.</u> If it's bad, replace that one, and you are done for a while. Of course you will choose as the first switch to remove and test the one you believe you use the most.

So what if the switch you tested is good? Do you put it back? Well, you have to – you only bought one replacement. No, really, you didn't, you bought two, probably three or four. Are you going to put back a used switch when its mate has just failed? Change it. Now change the other – perhaps test it later. Done.

# FOUR WAYS

Over the years as a lecturer in electrical engineering, I have had a lot of students come to me just to chat, and often to ask non-class-related questions.  A number of these were to inquire as how a "two-way" switch worked, and was it possible to do a "three-way". (Make your own assumptions about why they didn't ask professors this question).  Then it was a matter of explaining that the "two-way" was called a "three-way" and how it worked (Fig. 2).  That made sense.  So how do you do the four-way?  Not like Fig. 12.

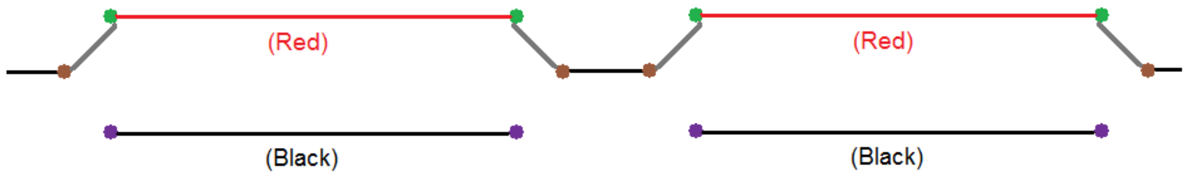



Fig. 12  You Can't Just Cascade Three-Ways

Well, you can't just cascade two three-way setups (Fig. 12), perhaps supposing that you get four switches total.  Indeed, with the switches as shown in Fig. 12, any one switch will turn OFF the light.  But then only two of the four (including the one you just turned OFF) will turn it back on.  But we do have pretty much the switching structures we need. You need a Double-Pole Double-Throw switch (well almost). This is seen in Fig. 13.

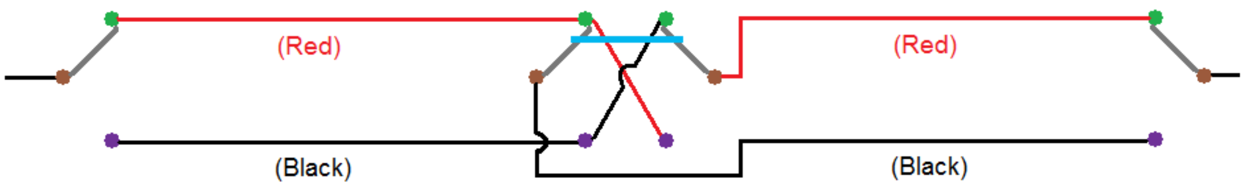



Fig. 13  You Use What Is Effectively A Double-Pole Double-Throw

This DPDT is like two SPDT switches side by side, with the activation levers connected (indicated by the blue strip).  We likely are familiar with this as a "six-terminal" panel-mount toggle DPDT device.  Note that the DPDT cross-over wiring here is classic, used to reverse polarity, or switch wires, which is what is being done here.  (Switching to the "other" wire is the same basic idea as the standard 3-way – switching the black wire to the red wire, and vice versa).  The DPDT shown in Fig. 13, with the switches UP as shown, changes the red and black wires moving from the left side to the right side.  With the switch levers DOWN, red is reconnected to red and black to black.  That's how it works.

Two additional points need to be made.

First, we are now in a position to add as many extra switches as we might desire. Just repeat the DPDT four-way in the middle additional times.

A second point is that as shown, we might expect that if we buy a “four-way” switch, it should have six terminals. It doesn’t – it has only four terminals. (Again, is that why it’s a “four way”?) This is because the cross-over of the outside terminals is wired in – you don’t have to do that every time yourself. Notice that while the switch as drawn has six terminals, there are only two wires in (left side) and two wires out (right side), so that’s four terminals total that are needed.