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Introduction

The aim of this guide is to provide the reader with a good basic understanding of the systems, standards, and principles of operation involved with theatre lighting systems so that they may be able to confidently set up and operate theatre lighting gear. Modern lighting equipment can sometimes appear daunting, not least owing to the sophisticated methods of control and software systems on which it often relies. However, this guide will demystify this and provide one with the necessary knowledge required in order to become acquainted with common equipment used in the “behind the scenes” area of a theatre.

The guide if split into two main sections: *Hardware* and *Software*. The former focuses on the physical technology used and the electrical principles of operation and connection thereof whereas the latter discusses the more detailed operation of and how to operate computerised digital devices such as lighting desks - a skill which is also equally essential if one is to have a decent grasp of how to operate theatre lighting equipment. The latter also discusses the detailed modes of operation of digital software-based signal transmission standards.

Each of the two overall sections is split into logical chapters. The guide can therefore be followed as a linear chronology or reference can be made to specific sections/chapters.

It is noteworthy that various roles come under the category of “stage lighting” since a lighting control console is also responsible for operating devices such as smoke, haze, and fire machines, all of which use the same signalling standard (see *Hardware 2: DMX Control*) as lighting units. As such, unless one is working in a very large theatre, the lighting operator/technician will often be responsible for configuring these units as well. Depending upon the number of personnel on the sound/audio-visual team, it may also be necessary for a lighting technician to set up some of the *hardware* required for sound or video in a production, even though this is strictly not a lighting-related role.

With regards to assumed prior knowledge, this guide assumes knowledge of electrical fundamentals (roughly secondary school GCSE-standard Maths/Physics), although the first section of *Hardware 1* is essentially a primer on conventional AC circuit theory. However, essentially no knowledge is assumed of the operation of equipment which is unique to theatrical venues.

Throughout the guide, green boxes may be found alongside certain sections of text:

These contain additional information ("useful note[s]") linking to the explanatory content on the main page. Synoptic links between sections are also made by this means.

Similarly, the reader may also find orange boxes:

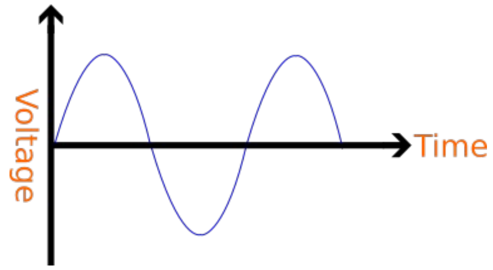
These contain cautions about common hazards or misconceptions regarding a particular concept or piece of apparatus. Safety aspects are also stated by this means.

Hardware 1: Introduction to Electrical Systems

In order to fully understand theatre technology, especially that which is used for lighting, it is very important to have a firm grasp of more general electrical systems and their principles of operation since these are closely intertwined with those of lighting devices.

H1.1 - Mains Electricity Theory of Operation:

Most buildings in Britain receive a mains electricity supply of 240v AC at 50Hz (50 cycles per second). This means that the current entering the building changes direction *50 times per second* between positive and negative directions of flow. If one plots a graph of how voltage fluctuates over time for alternating current, it will look like this:

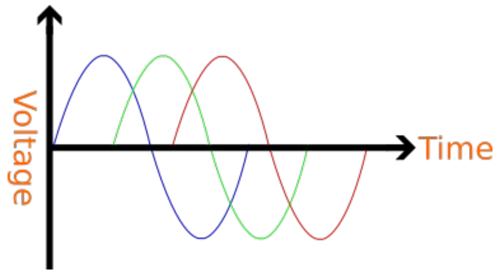


Useful Note:
See below for an explanation of how the 240v value is obtained for this constantly fluctuating voltage sine-wave.

This graph is called a *sine-wave* and is thus known owing to the fact that it is a plot of the fundamental function *y=sin(x)*, where "sin" is the trigonometric ratio sine. In the above plot, the top section represents positive voltage (current in one direction) and the bottom section represents negative voltage (current in the other direction).

Current is transmitted in this manner because it is more efficient to transmit electricity over long distances (such as from a power station in an isolated area to a city) using alternating current than using its counterpart: *direct current* - that which flows in one direction only.

Another highly important fact, especially when considering theatres, is that larger buildings which, unlike domestic properties, are likely to draw large amounts of current for stage lighting and similarly large apparatus receive a *three-phase electricity supply* along three separate live wires instead of one live wire as would be the case above:



One will notice that this graph of a three-phase supply is three of the above sine-waves but each one shifted a little to the right - 120^{o}, or 2.09 radians - along the horizontal axis from the previous one. For high-current applications (such as large buildings and appliances) it proves to be more economical to transmit electricity as three phases, as opposed to the simple *single-phase* (above) power since this allows for significantly more electrical power to be delivered to a building over thinner wires than would be required for the same amount of power over a single-phase supply.

If a voltage measurement is taken between any single phase of a three-phase supply and a 0v reference (neutral or ground; see H1.2 - *Introduction to Mains Electricity Hardware*), this individual phase-to-neutral voltage is 240v as is the case with a standard mains supply. However, if a voltage measurement is taken *between* two *phases*, such a phase-to-phase voltage reading will be seen to be 415v. This phenomenon can be explained, to a degree, by observing the three-phase graph shown on the previous page: the vertical difference between two phases, at any point in time where one such phase is at its maximum, is higher than the voltage between only a single phase and the 0v neutral reference (the horizontal axis) at the same instant.

Most of the time, upon entering a building, a three-phase supply will be split up into its three constituent phases, with each phase driving a single-phase 240v electrical load.

One will recall from above that single-phase mains voltage takes the form of a sine-wave at 240v. At this point, it is crucial to understand exactly how the 240v voltage value for mains voltage is obtained owing to the fact that a continuously fluctuating voltage does not ever maintain one single value, as shown in the graphs above. This means that some kind of mean or average must be taken in order to obtain a useful numerical value.

Two common misconceptions regarding the calculation of effective voltage delivered by an AC waveform are as follows:

i) That the 240v value is simply calculated by taking the single maximum magnitude of voltage reached by the peak/trough of one wave (i.e. the amplitude of the wave). This is not correct: the maximum level reached by a peak or trough of a 240v mains sine-wave is in reality ±325v;

ii) That the 240v value is calculated by taking a (preferably) high number of "samples" of consecutive values of voltage over the time spanned by one full wave and then simply calculating the arithmetic mean of these samples. This strategy will not work for the simple reason that the negative voltage samples (those below the x-axis) will exactly cancel out the positive voltage samples (those above the x-axis) with the result that the mean is uselessly calculated to be 0v.

As a result of the two problems highlighted by these two misconceptions, especially that in part (ii), it is evident that a procedure must be used which accounts for the negative voltages by retaining their magnitude without the aforementioned "cancel[ling] out" effect whilst also providing an indicative average value for the voltage.

To calculate the average voltage of a continuous mains-voltage sine-wave, a mathematical technique knows as *Root-Mean-Square* (RMS) is employed. The effectiveness of this method in eliminating the problem of the "cancelled out" sample values is reliant on the fact that the product of two negative numbers (or, indeed, the square of a single negative number) is always a positive number identical to that which is obtained by simply multiplying the two corresponding positive numbers together. By eliminating the negative sample values in this way, a mean can then be calculated.

The exact procedure used for an RMS voltage calculation is as follows:

i) A set of voltage samples is taken along one full wave (the more samples, the higher the accuracy of the resulting mean value will be);

ii) Each sample is squared. This creates a *solely positive* waveform (the negative samples have been "brought up" to the positive section) with a greater peak value (from the squaring action);

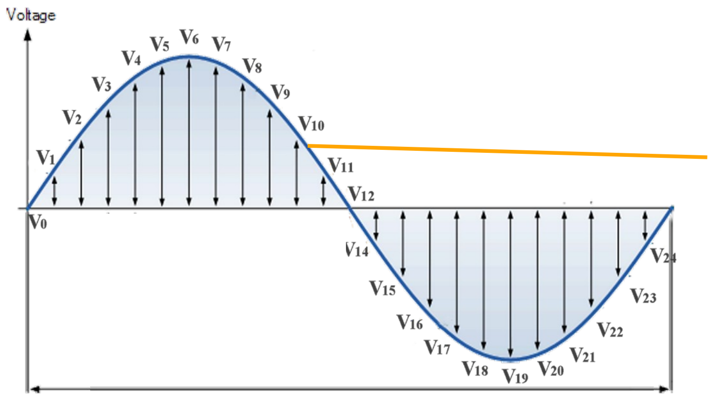
iii) A mean is now taken *using the squared values*. This means that no problem arises from negative samples: they have been "brought up" to a positive level;

iv) The mean calculated above is now square-rooted to "scale it down" owing to the fact that the samples were all initially squared - an action which must be undone in order to avoid the calculation of an erroneously high value.

This method of RMS calculation is one of the simplest and is reliant on a high number of "sample points" across a full wave in order to achieve a representative reading. The more samples are taken, the more accurate will be the calculated RMS voltage.

The abbreviation RMS is somewhat misleading owing to the fact that the actual necessary sequence of operations consists not of "Root-Mean-Square" but "Square-Mean-Root".

A Graphical Representation of a sampled sine-wave is shown below:



A number of voltage samples (*V0* etc.) are taken throughout one wave. These are then squared and used to calculate an RMS average voltage.

The following formula succinctly summarises the RMS calculation procedure:

Average voltage

$$V_{RMS} = \sqrt{\frac{1}{n_{samples}}\left(V_1^2 + V_2^2 + V_3^2 + \ldots + V_n^2\right)}$$

Sum of the squares of *n* voltage samples.

Divide by total number of voltage samples.

From this, it is clear that an increasing number of voltage sample points will lead to enhanced accuracy in the RMS value, albeit by a very small degree as one continues to add a high number of samples. If an infinite number of samples is taken, the truly accurate RMS value will be obtained. Of course, in practice, using an infinite number of samples in the above formula is clearly impossible. However, by calculus, it is possible to obtain this true value using the process of *integration*.

Integration is a means of finding the exact area between a section of a graphical curve and the horizontal axis for a graph to which one knows the equation. The process can easily be adapted to be of use in truly accurate (not sample-based) RMS voltage calculation: it ascertains towards what true value the RMS voltage *tends* as the number of samples reaches infinity, thus approaching the true area under the curve between two specified parameters on the horizontal axis. The aspect of area becomes important in *Hardware 3.*

Since mains voltage takes the form of a sine-wave, its equation can be seen to be:

$$y=325\sin(x)$$

Where *sin(x)* refers to a simple sine-wave which simply oscillates between 1 and -1 and where the 325 coefficient increases the amplitude to the real mains voltage level.

Since integrating a graphical function gives the area between the function's curve and the horizontal axis *for a specified x-axis range,* integrating a standard sine function of the above sort results in the following formula:

$$\int_{T_1}^{T_2} 325\sin(x)\,dx=[-325\cos(x)+c]_{T1}^{T2}$$

Useful Note:
The *x* parameters *T1* and *T2* are chosen such that one full oscillation - the period of the function - is selected.

However, the RMS mean is taken not from a standard sine-wave, but using a *squared* sine-wave - the pattern obtained by squaring each of the "samples" used on the previous page. The equation for a squared sine-wave is therefore:

$$y=(325\sin(x))^2$$

It is therefore the case that, from this equation, its integral, when taken between time parameters *T1* and *T2* is as follows:

$$\int_{T_1}^{T_2} (325\sin(x))^2\,dx=\left[\frac{105625(x-\sin(x)\cos(x))}{2}+c\right]_{T1}^{T2}$$

This formula corresponds to the sum of an infinite number of the aforementioned "voltage samples" - exactly equal to the area along the *T1* to *T2* range. This integral can be substituted into the sample-based RMS voltage calculation method thus:

$$V_{RMS}=\sqrt{\frac{1}{T_2-T_1}\int_{T_1}^{T_2}(325\sin(x))^2\,dx}$$

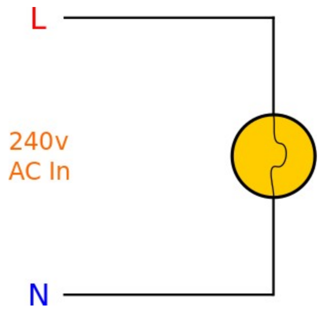
Whilst these expressions are mathematically true, in reality, the unit "time" which is assumed in this section for the horizontal (*x*) axis is somewhat ambiguous. This is because the trigonometric ratio sine requires some kind of angle unit (typically radians - 2π radians correspond to 360 degrees, or one full oscillation of the sine graph) in order to produce the expected oscillating pattern. It is therefore the case that a coefficient accounting for angle units (generally radians) and also for the production of a correct frequency is placed in front of *x* inside the *sin* function. A mains sine-wave oscillates at 50Hz and will therefore require an *x* coefficient of 100π (50x2π). The addition of such constants for a sine-wave of a particular frequency will correspondingly affect the above expressions, but the overall procedures remain accurate.

H1.2 - Introduction to Mains Electricity Hardware

There are various different pieces of electrical hardware which are commonly used in buildings with which it is worthwhile being acquainted. Most simply, one must note that the electricity entering a large building does so along three so-called *live* wires (or one wire, if a single-phase supply is being used). However, all modern electrical installations have two more wires: the *neutral* wire and the *earth* wire.

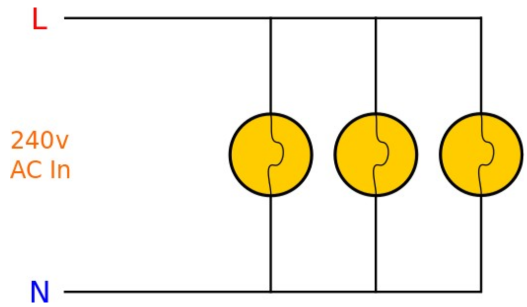
From GCSE-level physics, one will know that electricity requires a *complete loop* (through two wires - one entering and one leaving the load) to complete a circuit. In the case of a simple single-phase electrical installation, one of these conductors will be the live wire (on which a voltage, generally 240v, is present) and the other will be the neutral wire, on which there is no voltage but which is essential to complete an electrical circuit in conjunction with the live wire since the electricity (flow of electrons) must be provided with an adequate return path for a complete flow of current.

Below is shown a simple single-phase electrical schematic illustrating a connection to a light bulb. The live terminal (red) provides 240v AC power which flows through the circuit, including the light bulb, and returns via the neutral (blue) which is at 0v potential. The AC nature of the supply means that the electric current flows through the circuit from the live terminal in one direction momentarily and next flows through the live terminal momentarily in the opposite direction. This rate of oscillation is 50Hz:



Useful Note:
The live terminal may be considered to be “pushing” and “pulling” the electron flow through the circuit at an oscillation rate of 50Hz. The neutral is always at 0v and does not do any “pushing”/”pulling”.

If it were desirable to illuminate more than one light bulb from a single-phase supply, each may be wired in *parallel* across the live and neutral connection as shown below:

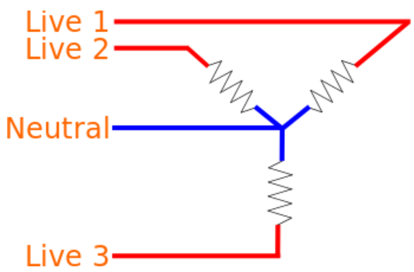


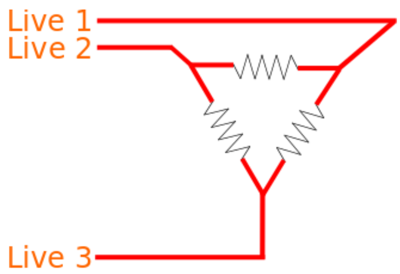
This arrangement means that each bulb receives the *full mains voltage* and therefore illuminates at its full intensity. This is unlike the effect achieved by placing the three bulbs in series with each other which would result in each one illuminating at one third of its full intensity. In parallel, the branches initially emerging directly from the power source to the point where they link to the leftmost lamp (from the red and blue circles to the first junction) must be rated to carry three times the electrical current of a single bulb: three bulbs are drawing full power through them. For example, if a single bulb is rated at 60W, three bulbs in parallel will require 180W - three times as much power - from the main supply cabling.

One may wonder what sort of a wiring arrangement with regards to the neutral connection is used in a three-phase electrical installation owing to the presence of three live conductors, one for each phase. The answer is that all three phases share the same common neutral connection. This means that the voltage between any one phase and neutral is 240v and a single-phase load can thus be driven with ease if necessary.

One must also note that, in spite of the fact that the three phases and neutral can be used (and indeed most three-phase devices will use the three live wires and a neutral), another arrangement exists where only the three live phase wires are used to drive a load *with no neutral.* This is commonly used for three-phase motors or heaters and operates as shown in the proceeding picture.

Below: A pair of schematic diagrams of the wiring of a typical three-phase supply (the zig-zag coils represent an electrical load on each phase) in the two aforementioned configurations:





One can see here that, for the latter, right-hand situation, the three phases meet *against each other* as opposed to all meeting at a common neutral as is the case in the former (shown left). The advantage of this is that less copper need be used for transmission because no neutral conductor is needed and also that the voltage difference between two phases is a higher 415v (see H1.1 - *Mains Electricity Theory of Operation*) as opposed to the 240v voltage difference between any single phase and neutral as would be the case in the former state. With regards to names, the former standard is known as three-phase *star* topology, since the wires all meet at a common neutral to form a star shape. The latter, however, is known as three-phase *delta* topology since the way in which the wires are arranged resembles the Greek capital letter delta (Δ).

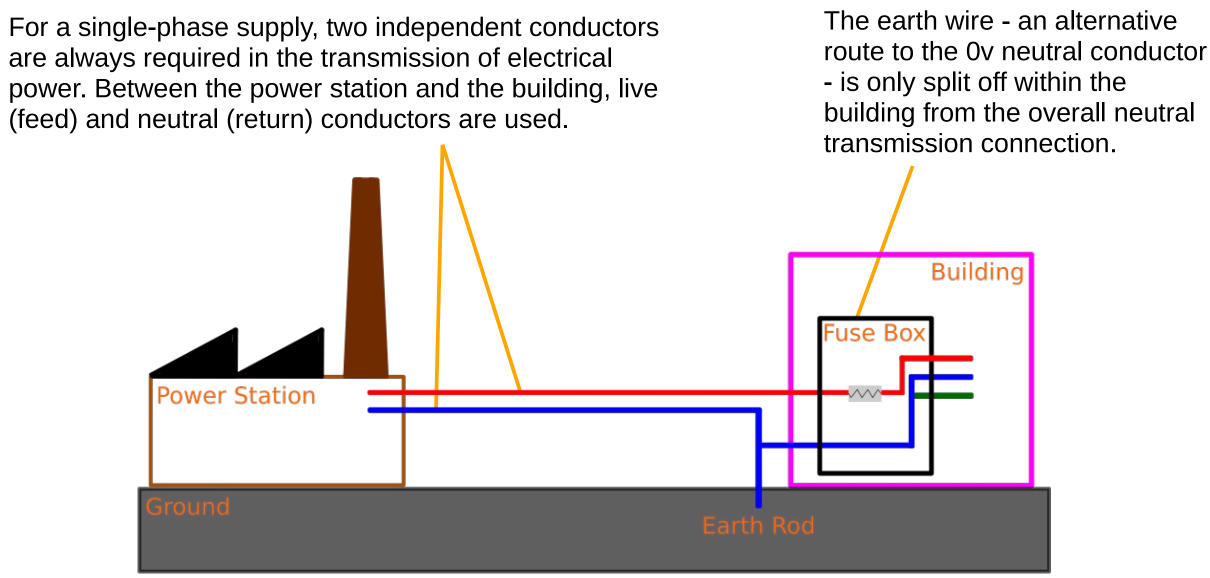
In addition to the aforementioned neutral wire, all modern electrical installations include one more wire: the *earth* wire. This is a safety precaution to protect against electric shock should a fault develop on an electrical appliance or installation.

One end of the earth wire is connected to the metal housing of an appliance and the other end is connected physically to the earth (the ground) through the building's structural metal framework (which, just like the neutral, is at 0v potential and thus provides a pathway for complete flow of electricity from any live conductor).

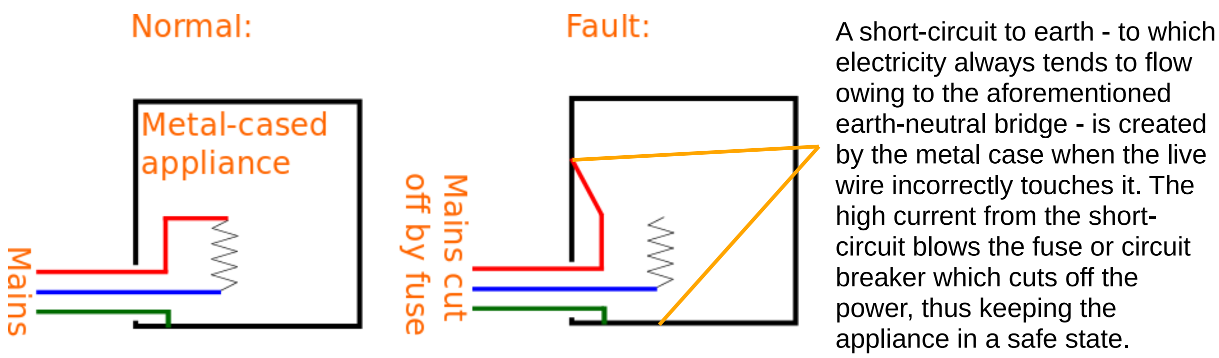
Important Note:
The fact that earth and neutral are both at 0v potential means that often, in the wires running from a power (or sub-) station to a property, *only one or the other* is used: they both provide a return path for the complete flow of electric current. The split to the neutral and earth wires only happens at the property's main fuse box – the only point where the safety of the additional earth wire is needed.

The end of the earth wire which is connected to the appliance's housing is not normally electrically connected to any live terminal since the neutral connection is the primary return path for electric current. However, if a fault develops and a live wire from the appliance's inner workings touches the outer metal casing, this is dangerous since the casing may now become live at mains voltage and could deliver an electric shock if someone touches it: their body provides the electricity with a path to the ground which, as mentioned earlier, is an adequate means of completing an electrical circuit. Therefore, to avoid such a scenario, the earth wire will provide an immediate short-circuit to ground through which a very large current will flow. Such a large current will result in any fuse or circuit breaker instantly cutting off current to the device, thus mitigating any risk of electric shock. Of course, if an appliance does not have any exposed metalwork (for example, if it is encased in plastic), it is said to be *double insulated* and does not require earthing. An earth connection is required by law on every domestic British power socket.

Below: a simplified (excluding electrical sub-stations) single-phase diagram of the electricity cables leading to a building. One can clearly see here how the single transmission earth/neutral splits to give an earth *and* a neutral wire downstream of the building's fuse box. Both are at 0v; an *earth rod,* driven into the ground close to the building, ensures that neutral, earth, and the ground, are all at the same potential. Blue corresponds to neutral, red to live, and green to earth. A three-phase supply would necessitate three red (live) wires leading to the building:



Below: a comparison diagram showing the purpose of the earth wire in an appliance. Blue corresponds to neutral, red to live, and green to earth. The coil represents the electrical load (i.e. a motor or heater) in the appliance. Appliances with no exposed metal casing typically do not require earthing unless they are likely to come into contact with water:



H1.3 - Power Distribution Hardware

Having now explored the general principles of mains electricity and its hardware, one can now focus on the electrical hardware used *within* buildings and with which the backstage theatre technician will inevitably have to work in order to successfully set up technical lighting equipment.

At the point where the electricity supply enters a building, one will find a *fuse box.* This is generally a covered metal box containing the equipment which splits up the electricity supply into the different *circuits* found in a building (those for lighting, sockets, electric stoves etc.) and includes protection against short-circuits or over-current faults, such as those described above in H1.2 when discussing earthing.

The term *fuse box* is nowadays something of a misnomer since most electrical installations use electromechanical *circuit breakers* to protect against over-current faults. Circuit breakers carry out the same task as fuses with a number of advantages:

Feature	Fuse	Circuit Breaker
Speed at which it breaks the circuit in the event of a fault.	Relatively slow (~0.1s)	Very fast (~10ms)
Does it need physical replacement after cutting off power?	Yes	No ("reset" button instantly restores the breaker to pre-fault state)
Ease of restoring power after a fault.	Tricky since one will have to reinstall a fuse or fuse wire manually in the fuse box.	Easy since one only needs to push the circuit breaker's reset button once the fault is cleared.

Inside a fuse box, one will find a *main switch* so that the user can manually isolate power to all the circuits simultaneously, a row of circuit breakers (each with its own toggle which switches the circuit on and off), and possibly a *residual current device (RCD)* which may be included to provide certain circuits with extra protection against earth leakage faults (see H1.2) in case a very high-resistance (low-current) fault to earth occurs which does not pass enough current to directly trip a circuit breaker or burn out a fuse.

An individual circuit breaker inside a fuse box typically consists of a rectangular plastic segment with a plastic switch toggle. This switch can be operated manually to control a circuit in a building (for example, a parallel-wired group of 13A square-pin sockets). However, if an over-current or short-circuit fault occurs on this circuit, the switch *automatically* "trips" to the off position with great speed such that electrical power is isolated from the faulty circuit and the extent of any damage or danger is minimised. The exact current which a circuit breaker can allow before cutting off power is determined by its rating in Amps (A). When installing a breaker, great care must be taken to ensure that the rating is high enough not to prevent rogue tripping from the nominal current draw of the load, but low enough such that dangerously high currents for the circuit's wiring are not allowed for prolonged periods.

A standard circuit breaker is wired "in line" to the live wire leading to a particular circuit - the neutral wire is not intercepted since it is at 0v and it is therefore better to break the circuit by cutting off the high-voltage incoming live wire in the event of a fault.

If a three-phase circuit is to be protected by a breaker, the procedure is exactly the same as above except for the fact that a three-phase circuit breaker, containing three rectangular segments, each with its own toggle, is used to intercept the three live wires leading to the load.

As mentioned in H1.2, the main fuse box is the point where the neutral wire entering a building is split to allow for the use of a protective earth wire inside the premises. After the split, the live wire goes through the relevant circuit breaker(s), the earth wire continues straight to the building’s earthed circuits, whilst the neutral wire, with the live wire, goes through a main residual current device (if present) which detects if any rogue current is leaking through the earth connection by comparing the difference in current between the live and neutral wires: both should be carrying the same “outbound” and “inbound” current if no earth leakage is present.

Below is shown a residual current device which is wired in a fuse box to further protect a group of circuits from any earth leakage faults. Note the fact that, unlike conventional circuit breakers, the live and neutral wires both pass through the RCD:

Two terminals are included for live *and* neutral wires.

Useful Note:
Under normal circumstances, the current through the live wire should exactly equal that returning through the neutral wire - the neutral is the only possible return. If current begins to find alternative “leakage” routes via the earth, *not all the current* through the live wire now returns via the neutral. The RCD detects this difference and shuts off power.

It is common for a three-phase supply to enter a building's fuse box and for each individual phase to then be assigned its own set of single-phase loads: the phase-neutral voltage is always equal to a standard 240v single-phase mains voltage. This means that the absence of three-phase circuit breakers in a fuse box does necessarily imply the absence of a three-phase supply.

Three-phase breakers may be encountered in a fuse box for fixed three-phase appliances or electrical three-phase socket outlets which are often found in theatres for powering high-current portable devices such as industrial electric heaters. A trio of three-phase circuit breakers is shown below, the leftmost one easily recognisable by the fact that it is three single-phase "segment" circuit breakers with their switch toggles joined together:

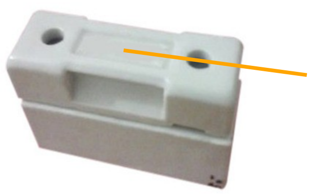
Three terminals are included for the three live wires of a three phase supply (the neutral, as mentioned before, doesn’t pass through a normal circuit breaker).

It is important that the current draw on each phase in a three-phase installation be as similar as possible to that on each of the other phases since if the phases are unbalanced with regards to their respective electrical loads, the neutral (see the *star topology* diagram in H1.2) carries a large current whereas if the load on each phase is the same, this “cancels out” the current on the neutral which is desirable to reduce the overall stress on an electrical system. It is also desirable to balance the load on the phases of an electrical supply since power companies will charge extra to buildings which have unbalanced phases since this puts more stress on the workings of their generators and transmission grid.

Important Note:
The problem of unbalanced phases will only occur significantly if the three phases of an electrical supply are split up to drive single-phase loads, since these can differ from each other in magnitude. Unbalanced phases will rarely occur from running a device which itself requires three phases.

In older buildings, it is likely that one will encounter a genuine fuse box with ceramic fuses used instead of circuit breakers. Inside a ceramic fuse cartridge is a thin wire which heats up resistively and burns out, thus breaking the circuit, if the current exceeds a certain limit. In most fuses, this wire can be replaced by the user. To do this, the fuse cartridge must be removed and the fastening screws which hold the thin wire in place undone so that the old wire can be removed. Finally, a new piece of fuse wire can be cut (ensuring that it is of the correct current rating as the old fuse wire; the circuit's rating will normally be written on the front of a fuse cartridge) and screwed into the cartridge.

Below: a picture of an old ceramic cartridge fuse:



The top section of this fuse can be pulled out of the fuse box to isolate a circuit or to replace the fuse wire inside it. The bottom section is permanently fixed into the fuse box.

There exist circuit breakers which can be installed in place of a fuse in a fuse-based fuse box in order to bring the advantages of circuit breakers to older hardware.

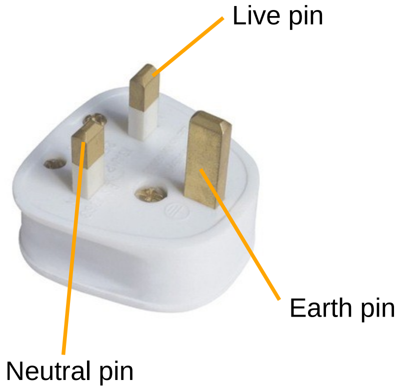
Important Note:
For a three-phase supply, a separate fuse is used for each phase. This means that, unlike a three-phase circuit breaker which breaks all three phases at once if a fault occurs *on any one*, a three-phase set of fuses will isolate only the single phase on which the fault occurs. This will still generally isolate three-phase devices and prevent them from working since they depend on all three phases.

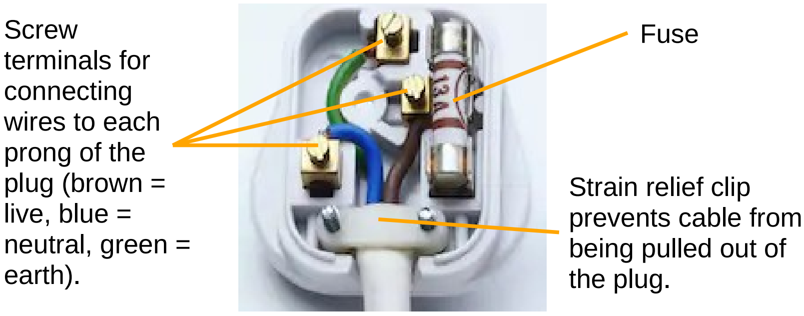
In very large electrical installations, it is likely that one will find a number of smaller fuse boxes dotted around the building, from which the building’s circuits are then run, owing to the fact that the total number of circuits in such a building would be so large that it would be impractical for them all to be fed from one enormous fuse box.

After the fuse box, electric cables will be run to devices such as electrical socket outlets (single- or three-phase), electric lights, stage lighting dimmers, and dedicated devices such as electric water/room heaters.

With regards to socket outlets, one will likely encounter three main types of socket/plug in a theatre for lighting purposes. The first, with which one will already be very familiar, is the standard British square-pin plug. This has a maximum current rating of thirteen amps and has a cartridge fuse (*not* a circuit breaker) inside it. The fuse inside a square-pin plug corresponds to the nominal current draw of the device. Such fuses most commonly come in ratings of 3A, 5A, and 13A and can be changed by removing the back of the plug.

Below: a British square-pin plug shown in its normal state (left) and with its cover removed (right):





The corresponding socket for a British square-pin plug will almost always have a switch to allow easy and safe isolation of appliances and is shown below:

Important Note:
For improved safety, a socket of this sort has internal shutters over the lower two holes - those which are live and neutral - which only open if an earth pin (top hole) is present. This is why the earth pin on a British plug is longer than the other two so that it enters its hole first, thus opening the two lower holes for the other two pins. This means that British plugs, unlike American or European types, always have an earth pin regardless of whether or not the device connected to them is double-insulated and actually needs earthing.

Ordinary, square-pin plugs will be used in almost any theatre or building for general utility power connection points. However, in some very old buildings (pre-1947, when British Standard BS1363 specified the creation of square-pin plugs), one may encounter *round-pin* plugs and sockets in place of square-pin alternatives. These plugs are typically of roughly the same size as a square-pin plug (although, unlike square-pin plugs, there exist smaller variants of round-pin plugs/sockets which have lower current ratings) but are capable of carrying up to 15A of current instead of the 13A maximum of a modern square-pin plug. It is also important to note that round-pin plugs *do not contain a fuse* and that therefore each round-pin socket in an old building will have its own dedicated fuse at the fuse box, unlike square-pin sockets, parallel-wired groups of which can share a fuse/circuit breaker in a fuse box.

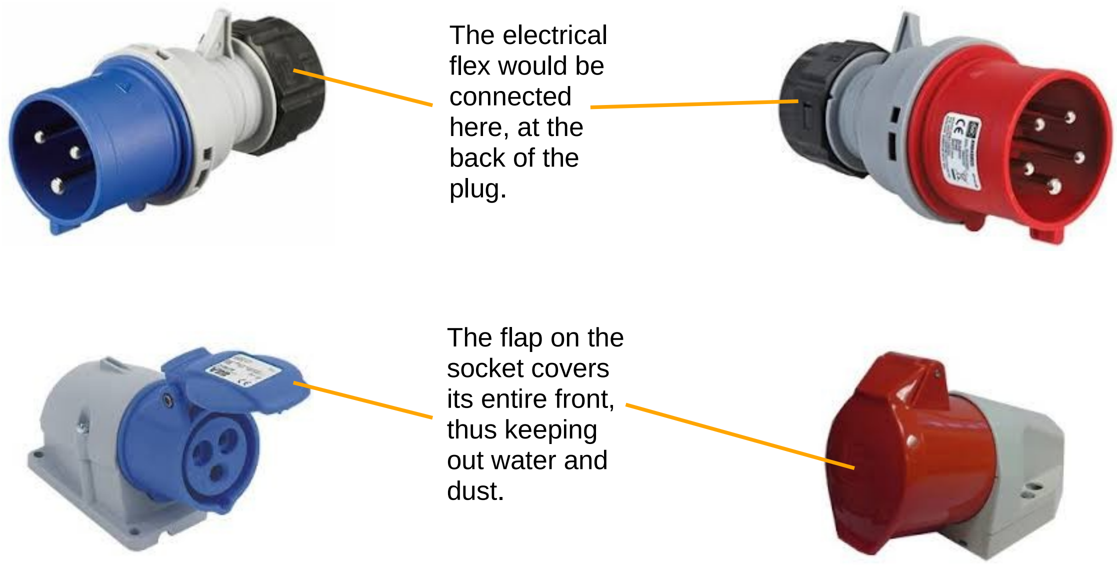
In spite of the fact that round-pin plugs are no longer permitted to be installed instead of square-pin plugs in buildings (although existing installations with round-pin sockets are sometimes permitted to use their existing sockets provided they are deemed safe with no clearly hazardous faults), they are still allowed for, and are a standard means of connecting, stage lights to lighting bars/dimmer packs (see *Hardware 3: Lighting Dimmers*). This is convenient because, in most modern installations, it prevents square-pin appliances being connected to dimmer-modulated stage lighting sockets and any subsequent damage which would ensue.

The second type of socket outlet which one will encounter in a theatre is the *CEEform (commando)* connector. This is a more industrial plug/socket arrangement which, unlike ordinary square-pin plugs, is waterproof to IP44 (splashproof) or IP67 (waterproof), can carry a current of up to 800A, and has no fuse in the plug; instead, each socket has its own circuit breaker in the fuse box, with sockets rarely connected in parallel groups. These plugs come in single- or three-phase styles, with the single-phase types being colour-coded blue and the three-phase types being colour-coded red.

CEEform plugs also differ significantly from standard square-pin plugs in the fact that they can come in a variety of physical sizes. The size reflects the plug's maximum current rating, with smaller plugs having a maximum current of 16A and the largest types having the aforementioned maximum current rating of 800A. Single-phase CEEform plugs have three pins (live, neutral, and earth) whereas three-phase CEEform plugs have either five pins (three lives, a neutral, and an earth) if a three-phase star topology is being employed or four pins (three lives and an earth) if a three-phase delta topology is being used instead.

From the point of view of safety, it is worth noting that CEEform sockets do not have the same shutter mechanism as square-pin sockets. Instead of shutters for each hole, a CEEform socket will have a spring-loaded lid over its entire front and which has to be manually pulled open in order to insert a plug. Furthermore, some CEEform plugs have a captive locking ring which is screwed tightly onto the socket once a plug has been inserted; this absolutely prevents the plug from working its way loose.

Below: a single-phase CEEform pair (left) and a three-phase CEEform pair (right):



CEEform plugs are largely used for connecting high-current devices such as exterior portacabins, lighting dimmer packs, and industrial electric heaters to a building's electricity supply. Unlike square-pin plugs, they are not designed to be connected and disconnected with great frequency because they require more force to mate together or pull apart. An example use would be the connection of a touring theatre's lighting dimmers to an electrical system for a few days.

The third connector with which one should be acquainted is the *Powercon* connector. The name of this connector is strictly that of a brand. These connectors have been introduced primarily for use in theatrical devices which plug into standard square-pin (non-dimmed) sockets and which need a suitable connector on the other end of their supply cable in order to connect to the device itself. One is generally unlikely to encounter *Powercon* sockets being used as hard-wired power outlet points in a building, in the same way as would be the case with CEEform and square-pin plugs/sockets.

The main advantage of this connector is that it has a very firm latching action when connecting to the device, meaning that there is no chance of the connector working its way out of its device device over time if located high up on a lighting gantry where it would be a nuisance to reconnect.

Below: a *Powercon* plug (right) and socket (left). The socket would typically be on the device to which the plug provides power:

The latch ensures that the connector does not come undone from the device.

In order to connect this type of connector, the plug is inserted into the socket and twisted clockwise until it latches with a distinct click. To disconnect, the catch is pulled back and the plug is twisted anticlockwise until it comes free from the device.

Powercon connectors are not waterproof and have a maximum current rating of 20A. Some variants may claim higher currents but will require proprietary sockets to fulfil this. The most common use for these connectors is to connect devices such as smoke machines or LED theatre lights - which are not powered from a dimmer pack - to the standard constant mains electricity supply.

Below: an example lead with a *Powercon* connector at one end and a small CEEform plug at the other end:

Important Note:
Powercon connectors only ever power single-phase loads. They also bear some similarity to *Speakcon* cables, which are used to connect certain types of loudspeakers to amplifiers. The position (“keying”) of the two circumferential notches is different for *Powercon* and *Speakon*; this prevents mains voltage from being applied directly to loudspeakers.

A useful connector in theatrical lighting contexts is the *Socapex* connector:

Socapex provides a useful means of connecting six separate power supply lines - each consisting of a live, a neutral, and an earth wire - as one connector. A multi-core cable is used between Socapex connectors; this allows for the six separate power supply lines to run neatly as a group over a given distance.

It is sometimes the case that a six-channel lighting dimmer pack, or power distribution unit more generally, will provide its six outputs by means of a single Socapex connector on the front panel. This means that one end of a Socapex cable can be used to neatly connect all of the pack’s outputs simultaneously. On the other end of the same cable, a 6-way splitter would typically be used to convert the grouped Socapex power connection to individual trailing sockets into which stage lights, or other powered equipment, may be connected.

Below: a close-up of a Socapex connector. The pins of this particular connector are labelled to show their function. Essentially, there are six groups of three pins (live, neutral, and earth) - one for each power supply line - arranged in a circle around the edge of the connector. Note that the centre pin is unused.

To round off this section about some common electrical connectors, a table of example scenarios is given below:

Scenario	Connector of Choice	Reasons
A smoke machine on a gantry is to be connected to the standard mains supply of a theatre.	*Powercon* [to smoke machine]/square-pin plug [to standard mains socket]	The smoke machine does not require a high current or a dimmed electricity supply and must also use a connector which will not come loose. The other end of the cable typically needs to connect to a standard socket for a supply of constant power.
A new dimmer pack is to be fitted in a theatre and connected to an electrical supply.	CEEform plug/socket	The dimmer pack will likely draw in the region of 20-60A when running under load and a high-current plug is therefore essential. The dimmer pack is unlikely to be moved very much but may need replacing in the future so it is preferable to provide a means of disconnection.
Six stage lights in close proximity to each other are to be each individually connected to a source of dimmed power.	Socapex lead between backstage dimmer pack and the group of stage lights	A Socapex cable provides a convenient and tidy way of distributing six connections between a dimmer pack and the group of stage lights. A 6-way Socapex-to-15A splitter can be used to “break out” the connection into separate 15A sockets into which the stage lights can be connected.
A vacuum cleaner is to be used.	Square-pin plug/socket	A vacuum cleaner is a domestic appliance and will therefore connect to a standard square-pin plug socket.
A conventional stage light is to be connected to a dimmer pack (assuming no different pre-existing patching arrangements; see H4.11 - *Patching Theatre Lights*).	Round-pin plug/socket	Round-pin plugs and sockets are a standard means of delivering dimmed power around a theatre. In all likelihood, the dimmer pack provides its dimmed outputs via round-pin sockets and the light fixture itself has a hard-wired flex, one end of which has a round-pin plug.

Within a theatre, it is always the case that technical appliances involved within a show, such as dimmer packs for stage lights, intelligent/LED stage lights, or smoke machines, will need to be controlled with ease. In order for this to be accomplished, a *console* (often referred to simply as a *lighting desk*), is used to centralise control of all the relevant devices in one place. From this console, it is possible to control all the lights and technical effects equipment used.

H2.1 - The Need for Control of Technical Theatre Appliances

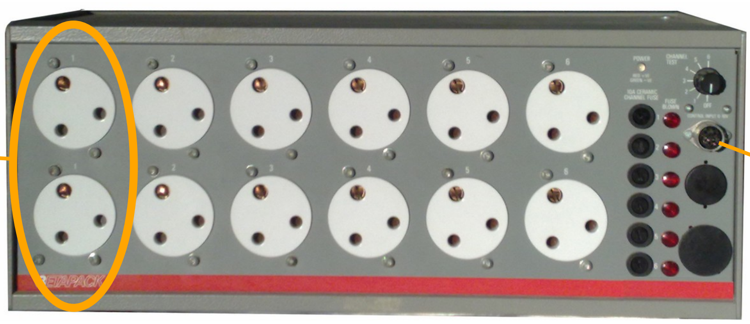
Fairly obviously, the central console has to have some means of signalling what the operator has input over to the appliances (generally lighting dimmer packs) to which it is connected.

Historically (pre-1986), many proprietary standards of signalling were used, depending upon the manufacturer of lighting equipment chosen by a theatre. The vast majority of these standards involved the sending of a specific 0-10v analogue DC voltage from the control console (located in the auditorium) to each channel of each individual dimmer pack (located backstage); each of these channels would then correspond to a (pair of) stage light(s). For each channel, the analogue voltage signal of 0-10v would be proportional to the high-voltage output (0-240v, in most cases) of that channel to its corresponding stage light.

Useful Note:
Although no industry standard for analogue control connectors exists, the most common type of connector used in analogue control cables is an 8-pin DIN connector of which only 7 pins are generally utilised (1 as a common ground, and the other 6 as the variable-voltage control signal wires).

Below: an analogue *Zero88 Betapack* dimmer pack. Each of the six channels (vertical pairs of sockets) would be controlled by a continuous 0-10v control signal over a dedicated wire. For a dimmer pack such as this one, a multi-core cable, with many separate copper wires enclosed in one bundle, would be used - each core carrying a signal for a different single channel. For more information about dimmer pack technology and the operation of analogue control signals, see *Hardware 3: Lighting Dimmers*:

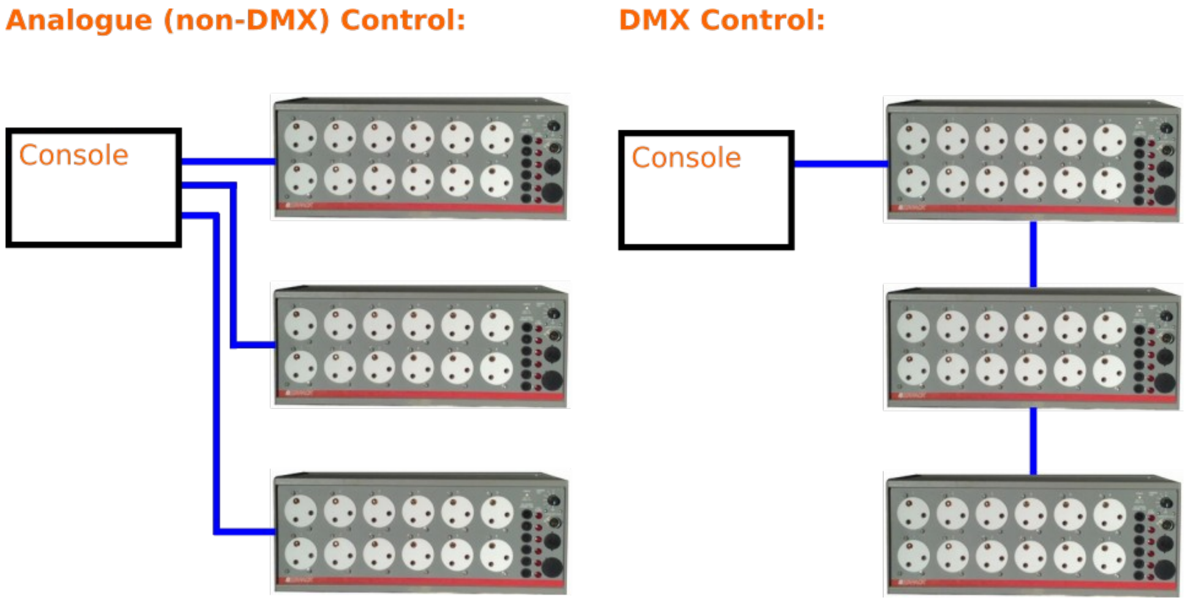
1 Channel controlled by a 0-10v control signal over a dedicated wire.



Multi-core cable, containing a control wire for each of the six channels, connects here via DIN connector.

Analogue control systems such as the one above all shared a number of disadvantages. First, a great many cables would be needed for a large number of dimmer packs (1 multi-core cable to each dimmer pack). This was generally not of concern to smaller establishments but became a problem in large-scale theatres which might easily have hundreds of dimmed channels. Second, no industry-standard protocol existed for connecting different types of dimmers and lighting consoles to each other, thus limiting versatility and ease of control if a theatre reached a situation where different types of dimmer packs/appliances from different manufacturers were to be controlled. Third, these systems were essentially exclusively orientated around controlling dimmer packs for *lights*, in spite of the fact that a theatre may also have devices such as smoke machines and similar special effects which it would be beneficial to control from the central console.

As a result of these disadvantages, an industry standard protocol called **D**igital **M**ultiple**x**ing 512 (DMX512, or simply DMX) was established in 1986. The main advantage of this protocol was that it allowed for *any* DMX dimmer packs to be *daisy-chained* from each other, with only one cable coming from the central console, and up to 512 channels of individual dimming (a dimmer pack such as the one below consists of six dimmed channels) controllable over this cable. This is shown in the below topological diagram, where a blue line indicates a data control cable:



Daisy-chaining dimmer pack controls through DMX proves highly useful in reducing the number of wires needed to carry control signals between backstage dimming gear and a lighting control console. Furthermore, the DMX protocol encodes dimmer data using *multiplexed digital* signals as opposed to individual analogue ones. Digital technology is, as a rule, less susceptible to data degradation and electromagnetic interference than analogue alternatives.

One must not be misled into thinking that the presence of a certain topological layout necessarily *implies* the presence of a particular analogue or digital transmission standard. Indeed, there do exist very rare analogue control systems, such as the *D54* protocol developed by *Strand Electric*, which still allow for dimmer packs to be daisy-chained. The defining feature of a daisy chain control topology is that each individual channel of control is not exclusively dependent on a single copper conductor wire; instead, a small number of copper conductors are used to carry dedicated multiplexed data to very many channels.

Useful Note:
Daisy-chaining data cables as is achieved in a DMX-based state of affairs is rather a rare phenomenon. Most electrical instances outside of the theatre industry generally employ a “star” communications topology such as that illustrated above left. Both IT networking and telephone systems, for example, are typically orientated around a “star” communications topology.

H2.2 - Principles of Operation of DMX Transmission

DMX transmits control data data using a serial digital (binary-encoded) transmission standard called RS485. This means that a DMX data cable only contains a minimum of *three copper cores* (unlike analogue control cables which require *one core per control channel*); the data is transmitted over these copper cores by repeatedly sending data for each channel of control in rapid succession. This also means that DMX data cables, discussed subsequently to this, can be thinner and simpler than multi-core analogue control cables in spite of the fact that one DMX cable can actually carry data to a greatly higher number of control channels than a single analogue control cable.

In essence, DMX channels are controlled from the console via the following procedure. The steps assume that each control channel consists of a simple dimmer parameter:

i) Each channel of control is allocated a unique identification number (*address*) from 1 to 512;

ii) The console (which is always the first device on the DMX daisy chain) rapidly sends a control signal to each channel address *consecutively* consisting of an 8-bit digitally encoded number between 0 (off) and 255 (full intensity);

iii) The console continuously distributes the aforementioned control signals to each channel of control at a rate of 44Hz (44 times per second). This means that each channel is "refreshed" 44 times per second and that even if a channel is in the "fully off" state, it is still receiving a signal 44 times per second - a binary-encoded number 0. The relatively high channel refresh rate means that any changes made on the console are seen, by a human observer, to take effect instantly on the lights being controlled from the backstage dimmer packs.

If, for example in a particularly large theatre, more than 512 channels of dimming (DMX's upper limit - also termed one "universe") are required, a console may be used which can output DMX data to *two or more daisy chains* (universes) of DMX devices.

The inherent daisy chain nature of the DMX protocol is such that the 44Hz-refreshed data *for every device on the universe* is received by every device connected to the universe. However, each device only samples a small section (determined by its identification address(es)) of such data which corresponds to each of its controllable parameters. For example, out of all the 512 addresses of control for a whole universe "moving through" a six-channel dimmer pack, it will only sample a group of six addresses within that range, one for each of its channels. The rest are ignored by that particular dimmer pack. Another six-channel dimmer pack on the same universe, on the other hand, will sample a different set of six addresses from the overall control data stream.

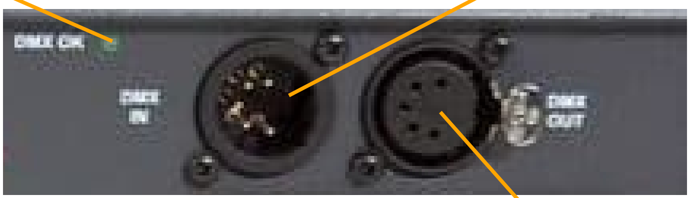
DMX is a particularly useful transmission protocol because it allows for the control, not only of simple dimmer packs, but of more complicated theatrical devices such as those discussed in *Hardware 5: Advanced DMX devices*.

H2.3 - Physical DMX Connectors

Next, we must explore the exact means of physical connection used for DMX data cables between a console and its controlled lighting equipment. Since DMX allows for devices to be daisy-chained, any DMX-controlled device (with the exception of the master control console, which is always at the start of the daisy chain) will have two DMX data connection points. These are termed "DMX in" and "DMX through". The purpose of the former is to accept an incoming signal from the console and the purpose of the latter is to allow this signal to carry on, through another cable, to the next device in the daisy chain. This is explained in the picture below:

"DMX OK" indicator light illuminates to show that DMX data is being received correctly.

"DMX IN" connector receives incoming DMX data through incoming DMX cable.



"DMX OUT" connector allows for a daisy chain to be continued from the same incoming cable through an outgoing cable to another device.

The industry standard connector for DMX devices is a 5-pin XLR connector, of which only three of the pins are generally used. XLR connectors come in a wide variety of pin numbers and also have a variety of applications; they are highly common in audio equipment, especially professional gear. The standard connector used for a DMX input (as shown above left) is a *male* connector whereas the standard connector used for a DMX output (as shown above right) is a *female* connector. It important that these standards be adhered to assembling connecting sockets and cables: maintenance of the correct standard will prevent two different DMX data lines from being connected together - an action which would likely result in a short-circuit. A 5-pin XLR cable is shown below:

Female end

Male end. Pins are protected by a metal sheath, thus giving the connectors enhanced durability.

Following on from the aforementioned aspect of 3-pin XLR connectors being used in audio applications, it is also highly important to note that some *non-compliant* (according to the original DMX512 standard) DMX devices also use male and female 3-pin XLR connectors as a means of connecting to a source of DMX control data. This is mainly the case owing to the slightly improved durability of 3-pin XLR connectors over their 5-pin counterparts. However, this non-compliant use of 3-pin connectors poses major risks of performance degradation, or even of malfunction.

Performance degradation can arise if 3-pin XLR *audio* cables (as opposed to dedicated, but non-compliant 3-pin *DMX* cables) are used to transmit DMX data between DMX devices: audio cables generally have a higher internal capacitance compared with dedicated DMX cables which can create timing problems with the DMX signal since, at 44Hz, any delay or time shift of the signal created by capacitance at any point in the daisy chain can create severe sampling co-ordination issues for the whole daisy chain of devices, thus opening up the potential for unpredictable operation of lights or similar connected devices.

At a minimum level, risks could manifest themselves through irritating confusion between audio cables and DMX cables, since 3-pin XLR cables are very common in professional and high-end consumer audio equipment. In a worst-case scenario, a 3-pin DMX cable could be connected to an audio cable carrying 48v "phantom power" intended to connect to a microphone. Since DMX devices normally use electrical signals no greater than 5v in magnitude, 48v phantom power could severely damage the DMX receiving circuitry not only in the next directly connected device, but in *every other device on the daisy chain,* since they are all linked over the same cable.

A further and even more extreme risk involves the fact that a number of online manufacturers of poorly constructed smoke machines are adopting the dubious practice of using 3-pin XLR connectors *as a means of transmitting mains electricity* at 240v to the smoke machine and a proprietary remote switch box. Clearly, XLR connectors are not rated for mains voltages; but these manufacturers generally utilise them owing to their low price and visually robust appearance. However, if a standard XLR cable were connected to a mains-voltage XLR socket of this kind, not only could the metal sheath around each end become live and deliver an electric shock, but any equipment mistakenly connected to the other end of the cable (for example, a lighting console, if it was thought that such a mains-voltage XLR connector was intended for DMX connection) could be severely damaged, even malfunctioning in a potentially explosive and therefore dangerous manner.

Below: the rear of a readily available smoke machine from *Amazon.co.uk* with an XLR socket which is used for mains-voltage transmission to a proprietary control switch (*not* standard DMX control). Image obtained from *Amazon* listing page via *https://tinyurl.com/uea2vhm*:

3-pin XLR socket used to transmit 240v power (*not* DMX data) through a “wired remote control” for semi-distant triggering of smoke release.

Hardware 3: Lighting Dimmers

Lighting dimmers and their corresponding stage lights form the backbone of many theatres. It is therefore important to have a firm understanding of the technologies used to achieve dimming effects. This chapter is complemented by the previous one, *Hardware 2: Introduction to DMX Control* for the simple reason that the DMX protocol is used to control many modern lighting dimmers in a convenient and flexible manner which is not possible with older, purely analogue, control methods.

The exact dimming circuitry described in the subsequent chapters of this section is orientated around analogue means of control for the sake of clarity of explanation. DMX-to-analogue conversion, as is now standard in any DMX-controllable dimmer pack, is discussed after that.

H3.1 - The Need for Dimmable Lights:

In any theatrical or stage-orientated lighting scenario, it is desirable that the lights have the potential to be dimmed. This can alter the created "mood" but also allows for the lights to be faded up or down to create smooth transitions between different lighting scenes as opposed to the sudden changes offered by simply switching certain lights on and off.

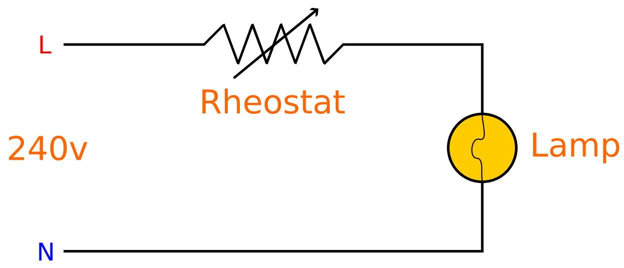
Theatre and similar professional environments are not the only applications where dimming may be desirable: many manufacturers of simple wall-mounted light switches for use in homes also produce wall-plate "dimmer switches" which allow for the intensity of the light bulb illuminating a particular room to be reduced from its full intensity to anywhere between that and zero.

Below: a common domestic rotary dimmer switch:

Such domestic dimmer switches are now becoming rarer owing to their general inability to correctly control modern low-energy light bulbs when such bulbs are used in place of the intended incandescent lamps. For theatrical purposes, however, incandescent lights are still commonplace owing to the fact that, unlike for use in the home, incandescent lights have not been banned for theatrical use by the European Union. For more information on theatrical lighting technology and fixtures see *Hardware 4: Theatre Stage Lights*.

H3.2 - Rheostat Lamp Dimmers:

The simplest way of dimming an incandescent light bulb is by placing it in series with a variable resistor, or rheostat. This means that, depending upon how the wiper of the variable resistor is adjusted, a large portion of the input power will be dissipated either by the resistor (with the bulb at a low intensity) or by the bulb itself (with the bulb at a high intensity). This arrangement follows that of a simple resistive voltage divider, with the supply voltage being split between the bulb and the variable resistor depending on their proportional resistances. A schematic diagram of this arrangement is shown below:



The main problem with this resistive method of dimming a light is the inherent inefficiency of such a system: when the lamp is at a low intensity, one would assume that, in such a state, the circuit should be drawing a minimal amount of current. In fact, with this arrangement, such is not the case owing to the fact that, with the bulb at a low intensity, the overall current draw remains identical to what it would be with the bulb at a high intensity, with the rheostat simply "burning off" the excess energy (that not being used to illuminate the bulb) as heat, leaving a lower proportion of the power available to the bulb with the result that the bulb is dimmer. When being used with high-power electrical supplies for similarly powerful lights, this excess heat creates a fire hazard if many such dimmers are being used.

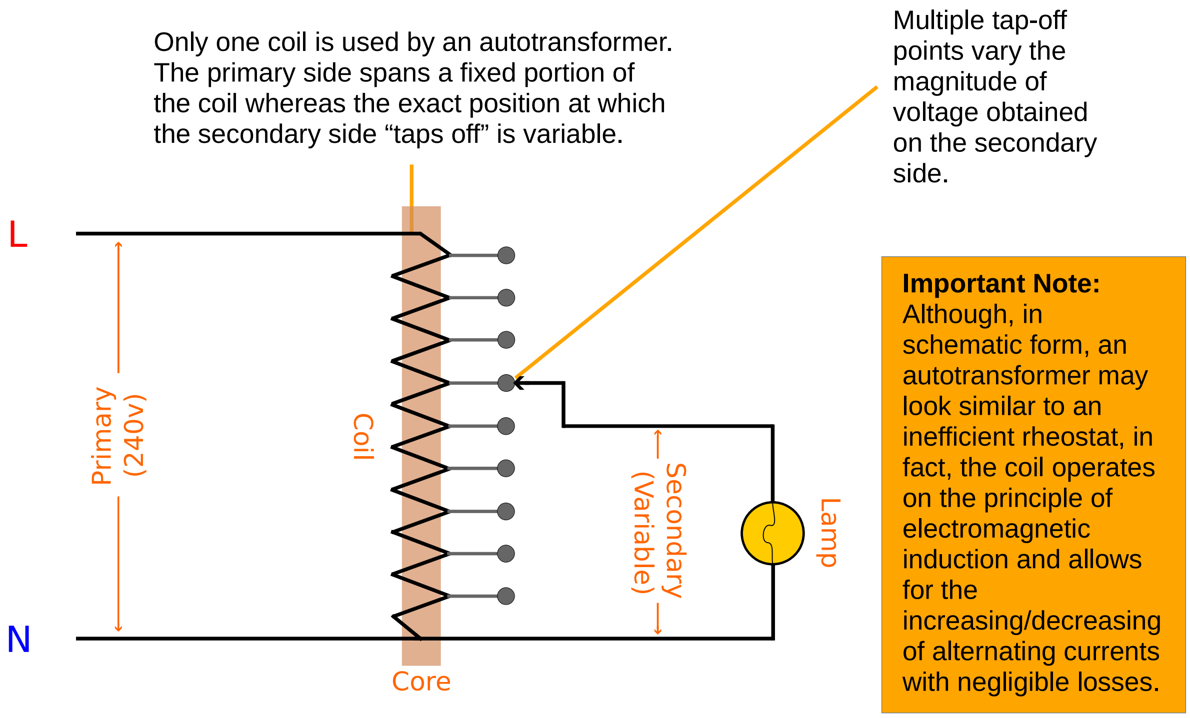
Another problem with this arrangement is the inability for it to be controlled at a distance: in a theatrical establishment, it is customary to control the large high-voltage dimmers at a distance from a relatively small console which operates only with safely low voltages. However, with a resistive dimming arrangement, this is impossible and every high-power rheostat for each dimmed light must be located in place of the console, thus creating the need for heavy high-current wires to be run between these and each dimmed light for which control is required. Furthermore, high-current rheostats are very large devices compared with the small "faders" found on modern lighting consoles, thus meaning that if a great many lights are to be controlled, the rheostat-based "console" may become impractically large.

An ideal dimming arrangement should consist of the large high-voltage dimming equipment located backstage (also most likely the point where the high-power electrical utility service enters the building, thus eliminating the need for bulky high-power cables to be run to the console location) with a small, low-voltage-operated console in the auditorium for safe and easy operation at a point from which one can see the stage. The console then sends low-voltage control signals to the backstage dimming equipment in order to adjust the intensity of desired dimmed channels.

H3.3 - Autotransformer Lamp Dimmers:

To address the inefficiency of resistive dimmers, an improved dimming system was later developed using variable *autotransformers*. An autotransformer is very similar to a standard electrical transformer for efficiently stepping up or stepping down alternating currents except that, unlike standard transformers, which consist of discrete primary and secondary windings, an autotransformer consists *solely of one winding* - portions of which act as both a primary coil and a secondary coil simultaneously. This winding is wrapped round an iron core as is the case with a standard transformer. The voltage obtained from an autotransformer can be adjusted by tapping off from the coil on the "secondary level" at different points.

A schematic diagram of a variable autotransformer is shown below. This very clearly illustrates the way in which a single coil acts as both the primary and secondary windings of a conventional transformer:



The ratio input voltage:output voltage may be calculated in exactly the same way as with a standard transformer, using the ratio of the numbers of "turns" allocated to the primary and secondary levels based on the position of the tap-off point:

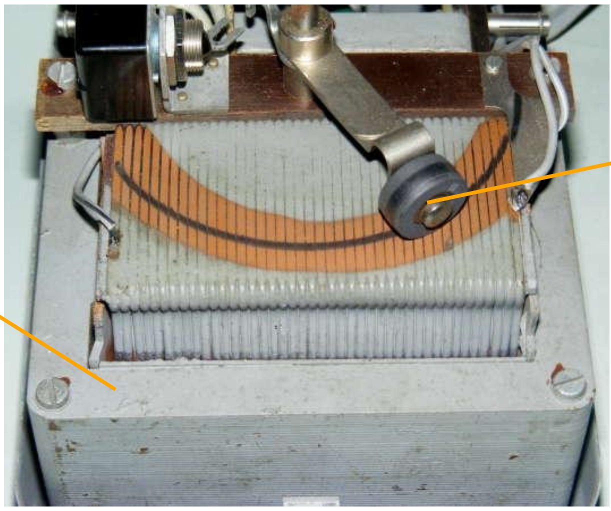
$$\frac{V_P}{V_S}=\frac{N_P}{N_S}$$

Where *Vp* and *Vs* refer to the voltages on the primary and secondary sides respectively, and *Np* and *Ns* refer to the number of turns on the primary and secondary coils respectively. Altering the tap-off point on the secondary side has the effect of changing the number of "turns" on the secondary level, thus altering the output voltage and adjusting the lamp's intensity.

In the above diagram, only a finite number of tap-off points are shown. However, by using a wiper contact for the secondary side, similar to that of a rheostat, to adjust the portion of the coil being energised, an infinitely variable output voltage may be obtained. This state of affairs is also termed a "Variac" - the name of the company which originally developed such variable autotransformers.

A photograph of a variable autotransformer with a wiper contact is shown below:

The *single coil* is wound around a ferromagnetic core, as is the case in an ordinary transformer.



Revolving wiper, following brown path over coils, acts as an infinite set of tap-off points for infinitely variable secondary voltage.

Unlike a rheostat, an autotransformer can be used to reduce the voltage applied to a light without the unnecessary dissipation of heat. The main difference which causes this is that the rheostat does not alter the supply voltage - simply what portion of that constant voltage's power it wastes as heat in order to dim the light, whereas a variable autotransformer genuinely alters the incoming supply voltage such that the current through the lamp may be reduced as a result, thus truly reducing the circuit's power consumption with the result that no wasted heat is produced.

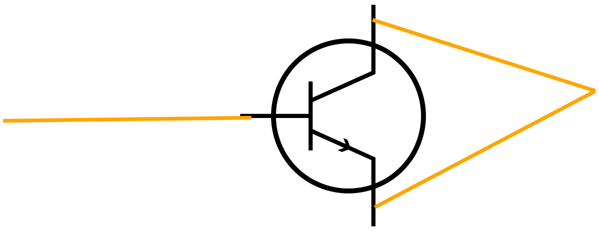
Although an improvement over simple resistive dimming technologies, variable autotransformers still lack the ability to be adjusted easily from a distance (one will recall from earlier that a desirable theatrical lighting arrangement consists of a separate control unit and dimmer array) since they still ultimately rely on the mechanical movement of a wiper over coils - the same motion as that of a rheostat. Of course, it is possible to provide a mechanical linkage between a console and Variac wipers over a distance by using gears or similar purely mechanical transmission methods to transmit a turning motion from the console to a backstage Variac but this will still add unnecessary complication to the required arrangement and may still result in a number of unwieldy mechanical control linkages. As such, since a superior means of dimming lights was still desired, semiconductor-based dimming technologies were introduced to address the aforementioned issues.

H3.4 - Phase Angle Semiconductor Lamp Dimmers:

A semiconductor is an electrical component which exhibits the characteristics of both an insulator against electric current and also of a conductor of electricity depending on the nature of its electrical input. For example, an elementary semiconductor component, the *transistor*, can conduct a proportionally large DC electric current through its primary electrical connectors (the "emitter" and "collector") when a comparatively small DC electric current is applied to its secondary "base" terminal:

Below: a circuit schematic symbol for a transistor:

A small electric current through this terminal results in the ability of the transistor to allow a comparatively *high* current through the other two terminals.



A proportionally large electric current is allowed through these two terminals when a small current is applied through the third (leftmost) terminal.

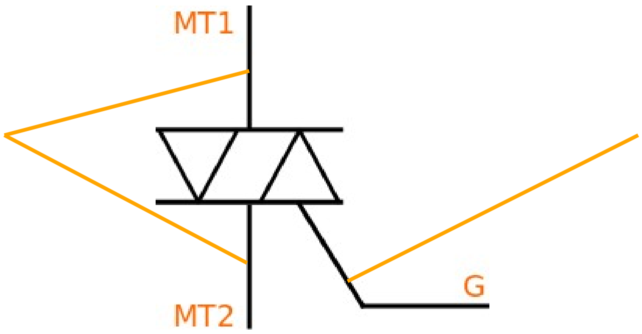
The mode of operation of a transistor can be considered to be greatly similar to that of a valve in a water pipe. The minimal turning of the valve (applying a small electric current to the third terminal) allows for a large flow of water through the pipes and valve (the primary two terminals).

Semiconductors are more robust than mechanical voltage control methods owing to their total lack of moving parts. They also have very rapid response times for applications which require the rapid switching of current (a synoptic example of this could be seen in the creation of digital DMX signals which require the encoding of 512 control data channels 44 times per second, as discussed in H2.2 - *Principles of Operation of DMX Transmission*).

The particular component used in lighting dimmers is a *triac.* This can be considered similar to a transistor except with an important difference: it only requires a small pulse of voltage to its secondary (gate) input and will *latch* the primary connectors into a conductive state such that they will conduct *even if the gate input voltage is subsequently removed.* After this, the only way to make it unlatch is by removing the voltage across the two primary pins (not the third gate pin). This binary "latching transistor" action makes triacs ideal for modulating alternating current, as discussed later in this section. Triacs, unlike transistors, are also capable of switching current flowing in *either direction*, thus further optimising them for switching bi-directional AC power.

Below: a circuit schematic symbol for a triac:

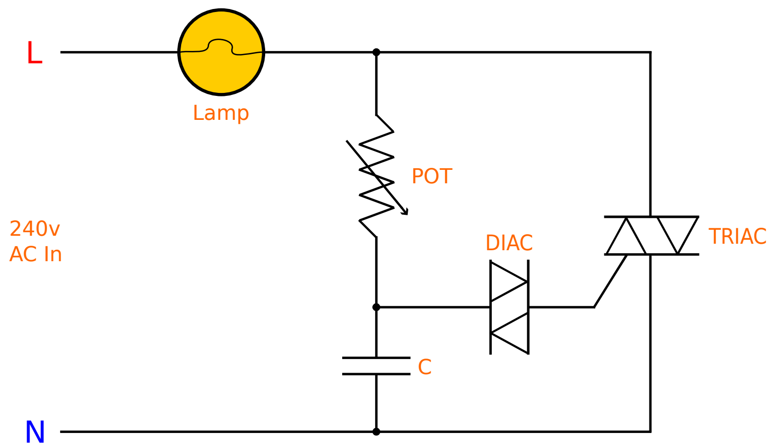
A large electric current is allowed through these two terminals when a small current is applied through the third (rightmost) terminal. Current continues to flow even if the third-terminal voltage is later removed.



A pulse of voltage through the third “gate” terminal latches the triac into a conductive state until the voltage across the main two pins (MT1 and MT2) is reduced to 0.

Another noteworthy aspect regarding triacs is that, somewhat unusually for semiconductors, they are designed to handle high-power electrical loads. This is important if they are to be used to control high-intensity incandescent stage lights.

The following schematic shows a basic circuit, such as that employed in domestic dimmer switches, which utilises a triac to adjust the intensity of an incandescent lamp:



The circuit contains the following components:

i) The *POT* (potentiometer) is a miniature variable resistor. This is used to alter the electric current through its branch of the circuit. Unlike the rheostat discussed earlier, the POT is *not directly responsible* for modulation of the lamp voltage and is therefore not a great source of wasted heat as with a rheostat dimmer;

ii) The *C* (capacitor) acts as a rapid store of electrical charge, taking a certain time period to charge up when electric current is applied to it;

iii) The *DIAC* (bi-directional trigger diode) must not be confused with the *TRIAC*. The diac's job is to conduct electric current into the triac's "gate" input only when its input voltage (from the tap-off point between the *POT* and *C*) reaches a certain threshold level. The time taken for the input voltage to reach this level is governed by the amount of time taken for the capacitor, *C*, to charge up, which is in turn governed by the setting of the potentiometer, *POT*: a lower electric current into *C* when the *POT* is set to a higher resistance will mean that it charges more slowly and therefore takes longer to reach the diac's minimum threshold voltage.

An easy way in which one can remember the difference between the diac and the triac, in spite of their almost identical circuit symbols, is through the fact that the **di**ac only has **two** electrical connections whereas the **tri**ac has **three** electrical connections.

It is important to note the fact that triac-based dimming circuitry only works correctly with an alternating current input. This is because the nature of the mains sine-wave, with its repeated zero crossing points of the horizontal axis (see H1.1 - *Mains Electricity Theory of Operation*) provides the triac with the requisite momentary lack of voltage across its main two pins which, as discussed above, is the only way in which it can "unlatch".

The operation of a triac lamp dimmer circuit can be summarised in the following stages:

i) At the start of an AC half-wave, the triac is unlatched and therefore restricting current flow. Current begins to flow into the capacitor, *C*, at a rate dictated by the setting on the potentiometer, *POT*. Negligible voltage is being delivered to the lamp;

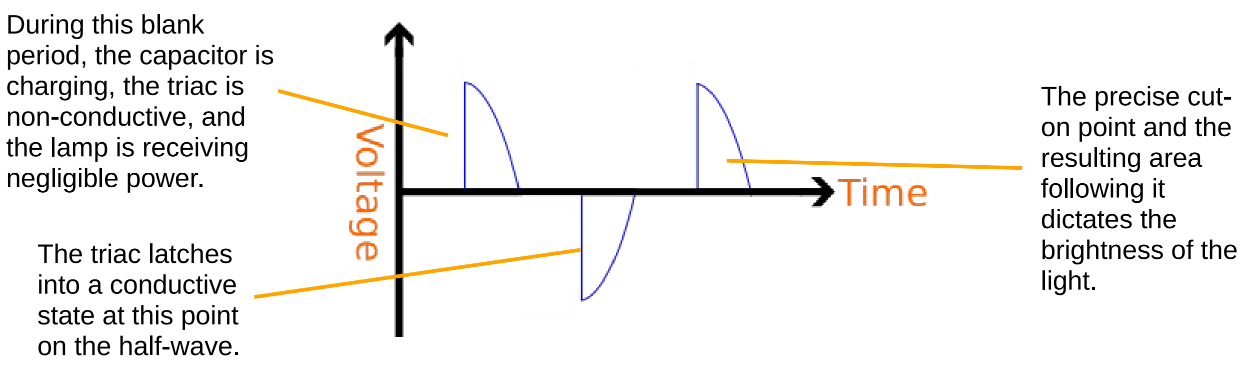
ii) As the capacitor, *C*, charges up, the voltage across it begins to increase as it draws progressively less and less current. This is analogous to a potential voltage divider;

iii) When the voltage across the capacitor, *C*, reaches the diac's threshold voltage (~32v), the diac begins to conduct electricity as the capacitor, *C*, discharges into the triac's "gate". This causes the main two terminals of the triac to latch into a conductive state. The lamp now comes on at a specific later point on the half-wave;

iv) When the half-wave reaches the zero crossing point, this de-energises the primary contacts of the triac, causing it to "unlatch". The process then repeats in the next half-wave;

v) By adjusting the resistance of the potentiometer, *POT,* the time taken for the capacitor, *C*, to charge can be reduced or increased. This alters the position of the "cut-on" point, or phase angle, on the horizontal axis of the waveform; if this point is closer to the start of a half-wave, the lamp is brighter since most of the half-wave area remains, whereas if it is further to the right, the lamp is dimmer: most of the area of the half-wave has been truncated thus reducing the RMS voltage.

The modified 50Hz waveform produced by such a circuit is shown below:



One may wonder why this extremely choppy waveform does not result in a visible flickering of the light. The answer to this is through the fact that this process happens twice in one full wave (100Hz) in conjunction with the fact that the high thermal inertia of the lamp's incandescent filament "irons out" the pulses of voltage to give a constant, lower-intensity, average light output.

In a theatrical context, this is a highly convenient method of dimming not only because it is efficient and reliable, but because the potentiometer, *POT*, for each dimmer circuit can be located far away from the backstage dimmer circuits in a compact console with only a thin low-current control wire leading backstage for each dimmed channel of control. In a simple analogue (not DMX-based) lighting console, each fader effectively acts as the *POT* for a backstage triac dimmer circuit.

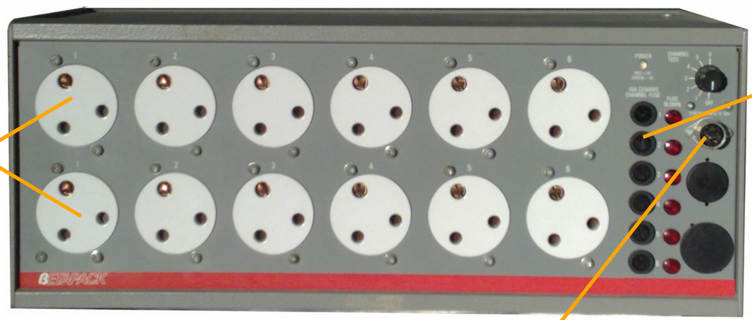
H3.5 - Theatrical Dimmer Packs:

Of course, the aforementioned dimmer circuit only produces one dimmed output. However, theatrical environments will require many more channels of controlled dimming. This is where so-called "dimmer packs" are used. A dimmer pack is, in essence, a backstage-located device which contains a large number (generally six) of triac dimming circuits similar to those in the previous section. An external connector is provided such that each circuit's potentiometer - the component which varies the degree of dimming - may be connected remotely from the dimmer itself by means of a distantly located lighting console's fader (for analogue control only - see below for DMX explanation). Sockets on the front of the unit allow for easy connection to stage lights. A high-current electrical input to the unit is achieved either by hard-wiring it into a building's electrical wiring, or by a 32A/63A CEEform connector. The dimmed output sockets from such a dimmer pack are generally provided by means of theatre-standard 15A round-pin sockets, although other connectors such as miniature (16A) CEEform sockets and *Powercon* connectors are also found on some modern dimmer packs.

Useful Note:
The triac system contained in a dimmer pack may differ somewhat from the most basic type shown in the previous section. This is because the previous circuit contains very little isolation between the mains and the potentiometer in order to prevent dangerously high voltages straying onto the remote console potentiometers. Theatrical dimmer packs contain additional isolation circuitry in order to ensure that the transmission potentiometer (or DMX, if present) connections to the console do not become dangerously live.

Below: a *Zero88 Betapack* dimmer pack:

Each dimmer circuit produces an output by means of a pair of theatre-standard sockets on the front of the device (1 channel).



A fuse (or in more modern dimmer packs, a circuit breaker) protects each channel from electrical overload.

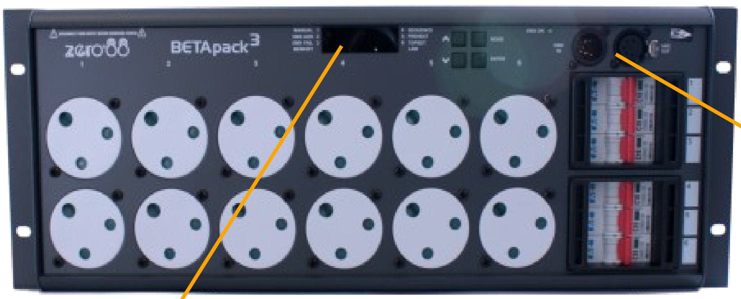
The multi-pin analogue control socket allows for the connection of externally located potentiometers (sliders) in a control console. These connect via six individual conductors, one for each channel. A common return conductor is also provided to carry out the task of the neutral wire in providing a complete circuit through each triac module and its corresponding slider potentiometer. This makes for a minimum of seven copper cores in the console-to-dimmer analogue control cable.

One will recall from *Hardware 2: Introduction to DMX Control*, that most modern theatrical equipment now communicates over the DMX protocol. This includes dimmer packs. One will also recall that DMX allows for dimmer packs to be daisy-chained and controlled over fewer cables than if each channel were directly connected to its own triac control potentiometer.

DMX dimmer packs are not controlled via a multi-core direct analogue electrical connection to the console. Instead, the digital control data sent by the console enters the dimmer pack through DMX XLR connectors and is *decoded* (based on its range of channel identification addresses: each channel of the multiplexed signal has its own identifier) inside the dimmer pack itself by circuitry which then produces the requisite potentiometer-style variable-voltage control output *within the dimmer pack* to operate the triac circuits. A "DMX Through" socket is always provided to allow for convenient daisy-chaining. A DMX dimmer pack is generally significantly more expensive than a simple direct-control analogue alternative owing to the comparatively complex digital-to-analogue conversion circuitry used to decode sections of the incoming digital signal to an analogue format which can control each channel's triac circuit.

In terms of their operation, it is the case that all dimmer packs are analogue with regards to their internal dimming action (a dimmed light is, after all, a continuous analogue output; certainly not a binary digital one). The presence of digital DMX capability does not mean that a dimmer pack is not analogue in terms of its dimming circuitry; instead, that it contains an internal DMX-to-analogue converter.

Below: a DMX-based *Zero88 Betapack 3* dimmer pack. Note the total absence of an analogue potentiometer-orientated DIN connector:



DMX *In* and *Through* connectors are provided for daisy-chained digital DMX control.

Since DMX is capable of controlling more than one dimmer pack, each channel (a dimmer pack such as this has 6 channels) is assigned its own unique address from the 0-512 address range. The digital screen and controls allow the user to select which DMX channel control addresses emanating from the console should control the six channels on the dimmer pack.

Fairly obviously, if a theatre desires to transition its lighting console from an analogue to a DMX-based type, it can prove highly expensive to replace existing functional simple analogue dimmer packs with DMX-capable models such as the one above. This is where a *demultimplexer* (or "demux") becomes of use. This is a device which receives a multiplexed DMX input from the control console and converts this into one or more legacy multi-pin analogue control outputs which can then be connected to traditional dimmer packs with no onboard provision for DMX decoding.

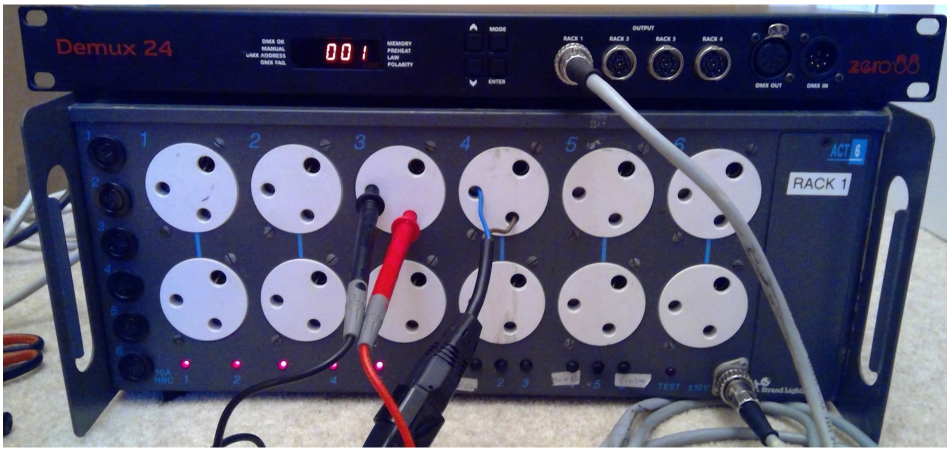
Below: a demultiplexer (*Zero88 Demux24*):

The digital circuitry decodes the DMX signal for a certain set of DMX addresses and produces an analogue voltage output, identical to that of a simple potentiometer, on each pin of each legacy DIN connector.

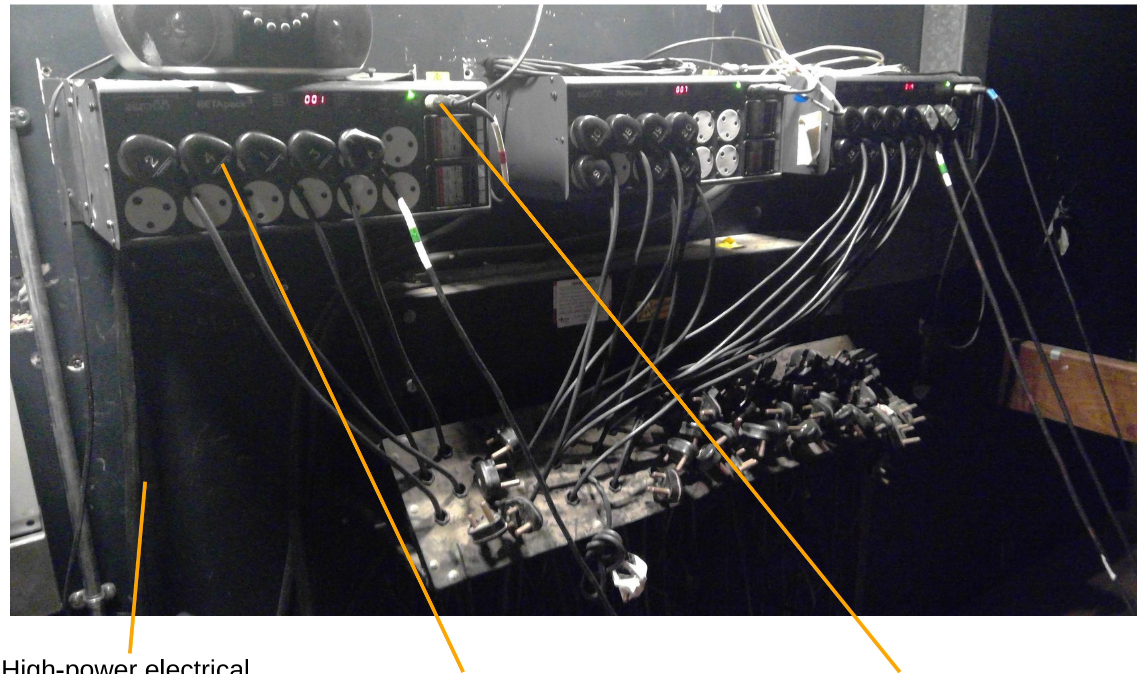
Analogue DIN sockets connect to legacy dimmer packs, providing them with traditional analogue control voltages for each channel.

A standard pair of DMX XLR sockets allows the device to receive multiplexed digital DMX data.

Below: a demultiplexer of the above kind connected to an analogue dimmer pack (*Strand Act 6+*). The wires inserted into the dimmer pack sockets are to test the output voltage. No DMX input to the demultiplexer is shown:



Below: a typical arrangement of backstage dimmer packs (*Zero88 Betapack 3*s):



H3.6 - Dimmer Laws:

The *law* of a dimmer refers to the way in which the rate of change of intensity of its light varies with the level of the control input signal, for example the movement of the potentiometer in the circuit shown in H3.4 - *Phase Angle Semiconductor Lamp Dimmers*.

In a standard mode of operation, a lamp dimmer has a *non-linear response*. This means that, in the case of a 0-255 DMX signal for one channel of dimming being sent from a console to a dimmer, although 0 corresponds to off and 255 to full intensity, the transitional intensity of the lamp is not exactly proportional to the actual numerical value on the DMX address of control. For example, if the console fader corresponding to such a light were slowly moved at a constant rate from 0% (address control signal: 0) to 100% (address control signal: 255), the intensity of the light would increase slowly towards the bottom and top of the fader's travel and quickly during the centre of its range. If the dimmer's response were plotted on a graph with DMX control input horizontally and light intensity vertically, the line would have a flatter gradient towards the origin and towards its upper end, and a steeper gradient at its centre. This line is referred to as an "S" curve owing to its shape.

This oddity can be explained by considering the mode of operation of triac dimmers. As discussed in H3.4 - *Phase Angle Semiconductor Lamp Dimmers*, a triac dimmer circuit truncates portions of each half-wave from the mains sine-wave in order to reduce the area of each half-wave and the resultant RMS voltage delivered to the lamp - RMS voltage depends on the integral of the wave (i.e. its area). Now at very low percentage levels, only a small portion of the half-wave may be left over from the triac cut-on point (see illustration of triac switching action in H3.4 - *Phase Angle Semiconductor Lamp Dimmers*). Since a very small end portion of the half-wave remains, the area between such a portion and the horizontal axis is low (see triac circuit output waveforms shown in H3.4 - *Phase Angle Semiconductor Lamp Dimmers*). This means that, if the dimmer fader is increased by a very small degree at a very low level, the corresponding increase in area brought about by the triac and its now-altered cut-on point is still low and the increase in light intensity is similarly low. However, if the fader is moved by the same small degree within the centre of its range, the triac is now adding area to the centre of the half-wave. Since the half-waves of the mains sine-wave are arch shaped, this means that any small movement in the cut-on point of the triac here brings about a large increase in area - that within the middle of the "arch" - compared with what would be achieved at each end of the arch-shaped half-wave. Larger increases in area for each degree of fader movement mean that the rate of change of light intensity is greater towards the centre of the fader's range.

This infinitesimal relationship between a small fader movement and the corresponding change in triac-modulated area of the half-wave may also be expressed using calculus, by taking derivatives from a graph of half-wave area (as modulated by the triac) against fader position (DMX signal). This procedure will result in a confirmation of the aforementioned "S" shaped, or "S-law" dimming curve. All triac-based dimmers produce an S-law output by default. For most environments which utilise triac dimmers, such as domestic dimmer switches for room lights, an S-law output is perfectly adequate.

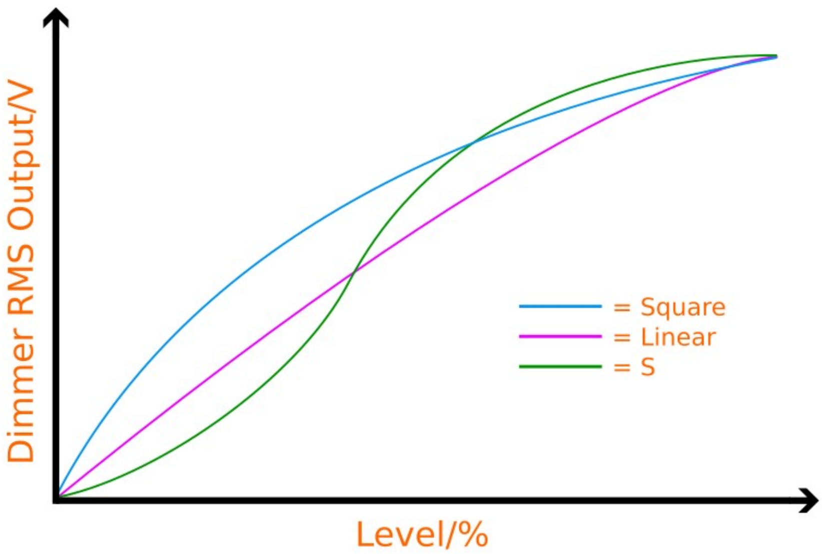
However, S-law dimming does not allow for the particularly precise control of lamp brightness in the middle range: a small fader movement in the middle region of travel results in a significant change in brightness. This may be undesirable for theatrical or televisual applications where a linear (or possibly even more different) response would be ideal. As a result, sophisticated dimmer packs may allow for the dimmer law to be altered between multiple different preset types. The dimmer pack then creates a small "fudge factor" on the incoming control signals such that the internal triacs respond to these signals in such a way as to bring about a more linear dimming response.

Dimmer laws are typically adjusted on multi-law dimmer packs themselves using integrated switches, miniature potentiometers, or digital controls. Sophisticated consoles also have the ability to alter the dimming law by directly introducing the aforementioned "fudge factor" directly onto their output DMX data. However, this method of adjusting the law via the console may prove less accurate than adjusting the law on the dimmer itself. This is because it is impossible to optimise the console's creation of the "fudge factor" for every subtly different triac dimming circuit.

The three most common types of dimmer law are as follows:

- S-law. Discussed above in great detail;
- Linear. The response of the light intensity compared with the incoming signal follows a somewhat straighter line;
- Square. As the fader is slowly faded up at a constant rate, the light increases in intensity quickly at the start, but much more slowly towards the end of the fader's travel. This law is useful for television studio lighting which requires precise control of lighting colour temperature towards the upper range of intensities - an aspect of control which is greatly enhanced by this type of law.

A graphical representation of the three main types of dimmer law is shown below through a graph of output dimmer voltage (light intensity) against DMX percentage level. Whereas the dimming response is highly variable for a basic S-law, it is largely linearised for a linear law, and further altered for a square law in order that the upper level region may offer finer dimming control:



Hardware 4: Theatre Stage Lights

Now that we have explored the technology used to physically connect and control theatrical equipment, we can now explore in greater depth the exact types and principles of operation of the physical stage lights themselves. This section mainly focuses on incandescent stage lights which are the most common type employed for this application.

A section is, however, dedicated to LED lights. Such lights are often used to supplement conventional incandescent fixtures but it must be noted that their modes of operation and control are very different to those of incandescent lights: they are never and must never be connected to dimmer packs in order to achieve control. Instead, each LED light receives a source of non-dimmed mains power and is controlled by daisy-chaining a DMX data line to *every individual LED fixture used*. This is different to incandescent lights, which receive a dimmed supply of voltage from discrete separate dimmer packs which are in turn themselves controlled via DMX.

H4.1 - Introduction to Electric Lights:

The definition of a "light" refers to any device which outputs useful visible radiation (light) from an inputted energy source; this is typically an electrical supply. Incandescent lights, which are the simplest and most common variety for theatrical purposes, achieve this by passing electric current through a thin metal wire (usually made of carbon or tungsten) enclosed in a glass capsule containing an inert gas atmosphere (typically argon or krypton) in order that the wire may not corrode. Now it is the case that any current-carrying wire heats up by a certain degree. If the diameter of the wire is reduced sufficiently, the aforementioned heating effect will cause the wire to glow white hot. This white glow is seen as useful light. However, the heat produced during this process is largely wasted energy, thus meaning that incandescent lamps have low efficiencies. This heat also causes the filament to eventually burn out ("blow") entirely.

An individual incandescent light bulb is shown below:

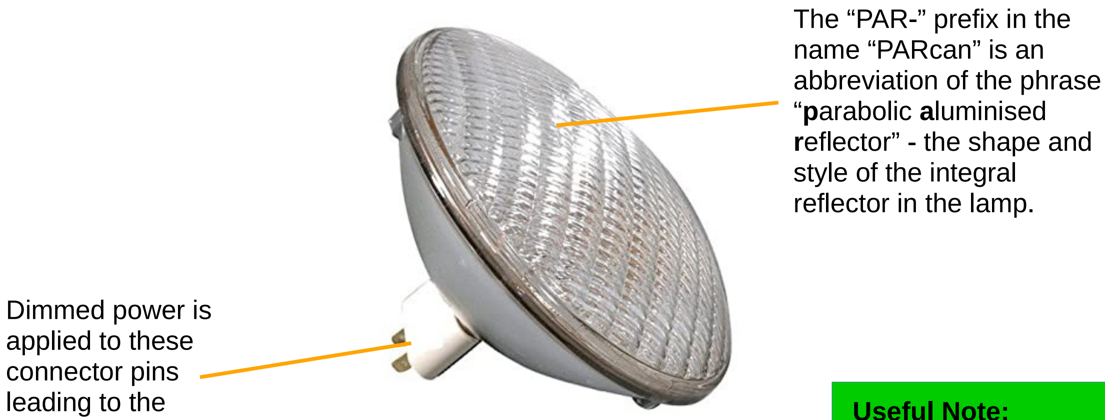
A typical incandescent lamp for use in domestic applications such as household room illumination is generally rated between 40w and 150w depending on the required light intensity. Such lamps are omnidirectional light sources which are generally placed high in a room to provide overall illumination. This means that for theatrical applications - which require directional, focused, light aimed at (specific points of) a stage - an incandescent lamp is not used alone but in a *fixture* which contains reflector and lens arrays to point the light in a more uniform direction. A number of varieties of fixture exist, each intended for a different ideal application.

H4.2 - PARcans:

The PARcan is one of the most basic and least efficient forms of theatrical stage light. It offers little control with regards to direction of light other than providing a roughly aimed "wash" of light towards a stage. Internally, a PARcan consists of an incandescent reflector lamp placed at the end of a cylindrical metal tube. The reflector in the lamp and the cylindrical tube (whose length may be adjusted to alter the amount of beam spread) serve to create a roughly directional beam of light for overall illumination.

Below: an annotated photograph of a PARcan fixture:

Below: a photograph of a lamp intended for use in a PARcan. The filament, reflector and glass housing are all one unit and must therefore be replaced together when the filament burns out:



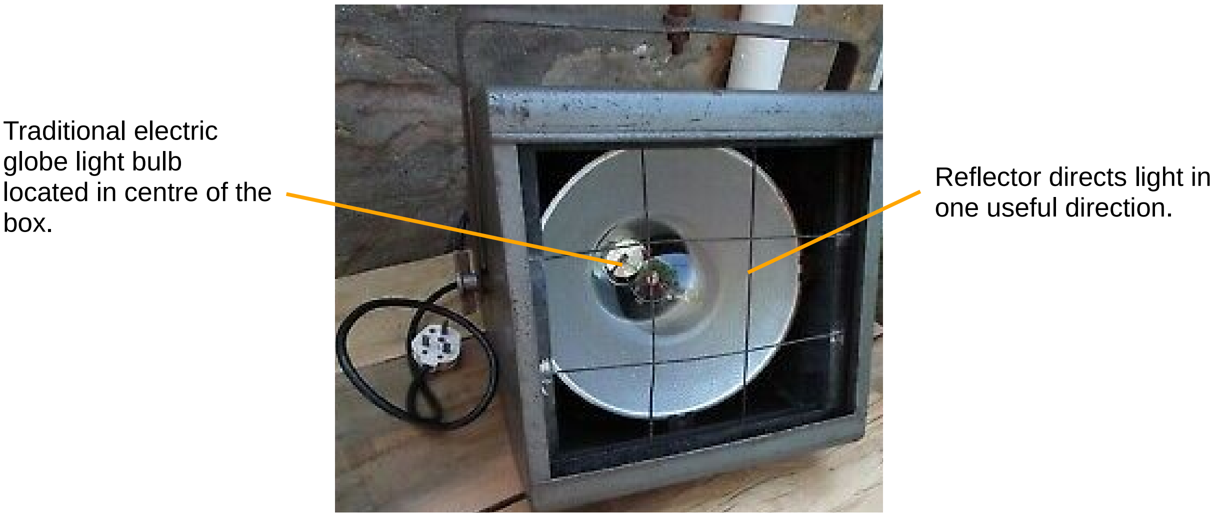
A number of different sizes of PAR lamp for use in PARcans exist. The designation numbers for such lamps range from PAR16 (smallest) to PAR64 (largest). In fact, these lamps were originally intended for use in early motorcar headlights but have since found further use in the theatre industry and also for some household lights. Size also affects the beam angle and overall light output. A lamp inside a medium-to-large PARcan is rated between 300w and 1000w. This is significantly more powerful than any domestic light bulb.

Useful Note:
PARcans' metallic bodies come in a variety of sizes to accommodate different sizes of reflector lamp. The smallest type of PARcan uses a PAR16 lamp – the smallest type available – which is essentially an alternative name for the popular 50w-rated GU10 halogen lamps often used for modern kitchen lighting in the home.

H4.3 - Box Floodlights:

Box floodlight, or box light fixtures can be considered similar to PARcans owing to a similarly low efficiency and limited control of light output direction. These fixtures are highly optimised for providing an even wash of light from *overhead* (for example, they may be suspended from lighting bars *above* a stage, pointing downwards, as opposed to other lights such as PARcans which may be aimed at the stage from a front-on angle) and may also be used for house lighting - that which is used to illuminate the auditorium space itself during periods such as an interval or before/after a show starts, when the audience requires some moderate illumination for convenience.

A box floodlight simply consists of a light bulb placed in a metal box with a reflector (separate from the bulb, unlike in a PARcan) to direct the light in a downwards direction. An annotated photograph of a box floodlight (*Strand Electric pat. 60*) is shown below:

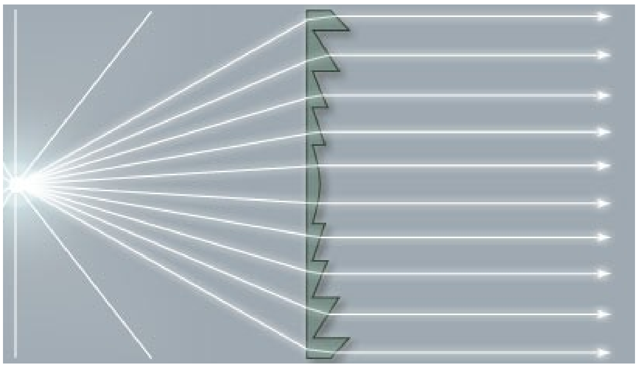


The lamp used in a box light such as this is similar to a household incandescent light bulb except that it is electrically and physically larger in order to achieve a greater light output. A photograph of such a bulb is shown below; observing this, one will notice clear similarities when compared with a conventional household light bulb:

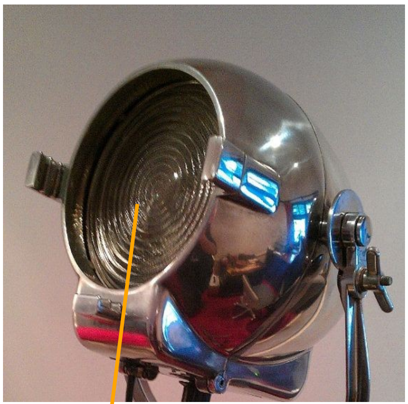
H4.4 - Fresnel Lights:

A Fresnel lens is named after its French inventor, Augustin-Jean Fresnel, who originally developed such lenses for directing the light output from lighthouses in a single useful direction. The great advantage of these lenses is that their stepped design means that they can be manufactured to be significantly thinner than a traditional concave/convex lens with the same focussing power.

Below: a diagram of a Fresnel lens. The rays from the point source of light are focused by a different degree depending upon which "step" of the lens they strike. The steps are angled such that the rays ultimately exit in one direction:



Fresnel light fixtures are thus named owing to their use of a Fresnel lens to create a directional light output. Inside such a fixture, a small but powerful capsule-shaped incandescent lamp acts as a point source of light in front of a separate reflector. The reflector directs the light rays towards a Fresnel lens located at the front of the fixture. The rays then leave the fixture in one direction. A Fresnel light from *Strand Electric* (left), in conjunction with its internal lamp (right), is shown below:



Characteristic stepped Fresnel lens creates a light output which is more directional than that achieved from either PARcans or box lights.

Useful Note:
Theatrical capsule lamps such as that above right are generally the most powerful varieties available. One may wonder, in light of the earlier commentary regarding the lamps used in a box light, how a capsule lamp such as this may fulfil its rating of 500w to 1000w without the glass melting. This is because it utilises quartz-based glass, similar to the toughened *Pyrex* glass popular in kitchenware.

H4.5 - Profile Lights:

Profile light fixtures are a very versatile variety of theatre lights, allowing for extremely focused, directional light, or a wider wash of light as required. They also contain a more traditional lens array consisting of concave/convex lenses placed at a distance, similar to the layout of lenses in an optical instrument such as a camera or telescope. The light output can be controlled in a highly specific manner owing to the presence of an *iris.* This is a set of flat metal plates within the fixture which can "chop off" certain portions of the beam of light outputted by the fixture in order to precisely illuminate certain sections of the stage.

Being more sophisticated than any of the aforementioned theatre lights, profile lights are also internally more complicated. A small capsule bulb, essentially identical to that used in a Fresnel light, is placed within the focal point of a parabolic reflector. The rays emerging from the reflector are then reduced by the iris - certain sections around the edge of the aperture are obscured by the iris's metal plates. Finally, the rays, having been reduced by the iris, are focused by a lens array and emerge from the fixture. It is also typically the case that the spacing of the lenses at the front of a profile light can be adjusted such that the overall area of stage illuminated by the fixture can also be adjusted by this means.

Through the presence of the iris and the adjustable lenses, profile lights are useful for a wide variety of lighting applications. They are generally optimised for "projecting" light towards a stage front-on, being largely unsuitable for overhead illumination.

A *Source 4* profile light - likely one of the most common models - is shown below:

H4.6 - Followspots:

Followspot lights (also simply termed "spotlights") are fixtures with a very narrow beam angle intended to specifically illuminate one (or very few) characters on a stage. They are typically manned by an operator such that they are panned or tilted to follow the path of an actor moving across a stage.

Many followspot lights can be seen to be very similar in construction to profile lights. However, the main differences are as follows:

i) Profile lights contain irises which allow for the beam to be reduced to any desired shape: the circular beam of light produced by the reflector is not necessarily maintained. However, followspots generally contain a more sophisticated iris which can be considered similar to the aperture adjustment device in a basic camera. This means that the beam of light produced by a followspot is always circular in nature, with the iris simply adjusting the diameter of such a circle;

ii) The lens array in a followspot is, by necessity, different to that in a profile light such that a significantly narrower beam of light is produced in order for it to be suitable for illuminating specific characters.

Since followspot lights are manned by a separate operator to the overall operator in charge of the main lighting control console, this operator is also generally in charge of turning his followspot light on or off (and, where necessary, dimming it) at the points during a show when it is needed. To accomplish this, the followspot is not connected to the main backstage dimmers (which, as discussed in *Hardware 3: Lighting Dimmers,* are controlled remotely from the central console) but to a source of constant power, such as a conventional square-pin utility socket. This power is then fed through a single-way dimmer module mounted to the stand or handle of the followspot, thus allowing it to be switched and dimmed by the operator.

A stand-mounted followspot light is shown below. Note the rear similarities in shape and style to a *Source 4* profile light such as that shown in the previous section:

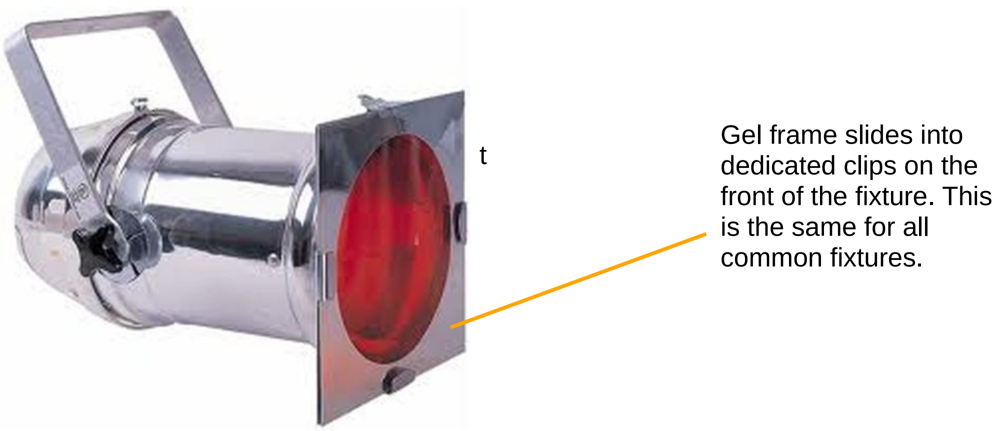
H4.7 - External Methods of Beam Adjustment and Alteration:

Once a fixture has been chosen for an aspect of theatrical stage lighting, it may be desirable to further alter the direction of light output (especially on fixtures which do not contain irises). Similarly, some shows may require that some lights be of different colours for enhanced effects.

A change in colour is obtained by placing a colour filter in front of the output of an incandescent fixture. Since incandescent light contains all the colours of the visible spectrum in its white light output, a filter simply restricts the wavelengths (colours) which are allowed to emerge. Theatrical colour filters are called "gels" and are based on a polymer construction.

Gels themselves are thin cellophane-like plastic sheets. As such, they require mounting in a simple metal frame, commonly called a gel holder. The gel sheet is cut to size depending on the type of fixture onto which it is to be mounted. It is then clipped into the fixture's gel holder. The gel holder then slides into the front of the fixture. It is important to note that different fixtures may require gel holders of different dimensions.

Below: a PARcan with a gel fitted in the front. The square metal frame around the coloured gel is the gel holder:

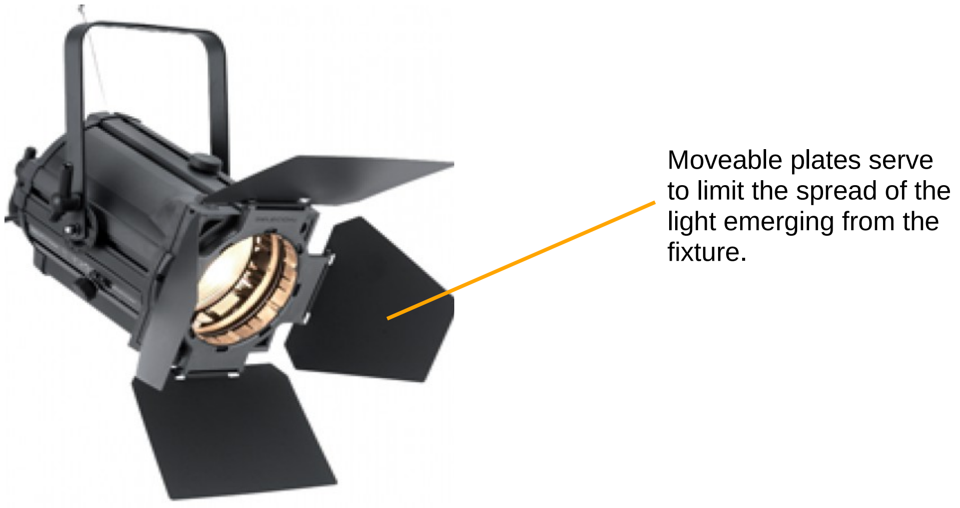


Although gels may look the same as simple pieces of coloured cellophane, they in fact have a significantly higher melting point than cellophane. This characteristic is of importance owing to the fact that incandescent light fixtures become very hot during operation. As a result, the use of standard cellophane in place of a proper gel will result in the undesirable melting of this inadequate "gel" in the front of the fixture.

Below: a selection of gel holders for a wide variety of fixtures of varying sizes:

As well as colour filters, devices can be fitted to the front end of lighting fixtures in order to limit the direction of light output. These are generally used on fixtures such as Fresnel lights or PARcans which have no integral irises to limit the region of illumination. Such devices are called *barndoors*.

Below is shown a barndoor array mounted to the front of a Fresnel fixture:



Further modification to the beam, similar in a way to that of the iris, can be achieved by using a GOBO. This term refers to a device which **go**es **b**efore **o**ptics. The "optics" term in the definition of a GOBO refers to the lens array. A GOBO consists of a thin metal sheet with a set of holes punched through it in strategic places such that a desired pattern is projected by the light once the rays, having been restricted by these holes, are focused by the optics.

Below is shown a GOBO which may be inserted into a fixture (typically a profile light since these have superior internal lens arrays, thus producing a sharper projected pattern). A projection pattern from another GOBO is also shown. Many different types of GOBO are available, including types with a custom-cut hole for a user-chosen pattern:

H4.8 - Moving-Head Light Fixtures:

Until this point, all of the fixtures discussed are stationary types. These are generally the most common type of lighting fixture used in theatres. However, they carry the disadvantage that, should they require movement once suspended in (possibly inaccessible) places, a technician must manually move and focus them, often by using ladders or scaffolding towers. This is of inconvenience if lights must regularly be moved and refocused when new productions are carried out; it is inevitably the case that different productions require different lighting effects.

These problems can be mitigated, at least to a degree, by using intelligent *moving-head* light fixtures. These are fixtures which contain a lamp, reflector, and lens array, but also electric motors to automatically pan or tilt the body of the light in a certain direction. Sophisticated models also include motors to adjust the spacing/position of the lenses or iris and also an automatic device to change the colour filter in front of the output. These motors can be controlled remotely from a central console over DMX. Of course, a more sophisticated control console may also be required since not only can moving-head lights be controlled with regards to their intensity, but also a plethora of other parameters (focus, pan, tilt, colour) - they are *multi-parameter* devices with a number of controllable aspects - which will be tricky to control with a standard dimmer console consisting exclusively of intensity faders (see *Software 2: Operating a Lighting Console*).

With regards to intensity control, it is also important to note that moving-head lights contain built-in dimming circuitry, thus meaning that they do not connect to dimmer packs but to constant power. For control, a DMX data cable is daisy-chained through every intelligent fixture in use such that each fixture's parameters can be individually controlled from the central console.

Below: a moving-head light:

Moving lights are rarely used alone but alongside conventional stationary lighting fixtures. They are highly optimised for so-called "special" lights for illuminating specific areas of a stage for small periods of time, often in different colours. Moving lights can also be illuminated *whilst* moving instead of simply repositioning the head whilst they are switched off; this is used for additional effects in theatres and is often favoured in the music/disco industries.

H4.9 - LED Light Fixtures:

Light-emitting diodes (LEDs) are a new, highly efficient variety of light source based around semiconductor chip technology. They are becoming commonplace for household lighting but are not used especially widely in the theatre industry. To further understand this lack of use, one must consider the fact that, unlike simple incandescent lamps, LEDs require substantial auxiliary circuitry in order to be run off even a normal mains supply.

LEDs require low-voltage direct current in order to operate correctly (around 3V per individual LED semiconductor). A mains LED light fixture must therefore contain circuitry to lower and rectify 240v AC mains power to a suitable level. The simplest means of lowering and rectifying mains voltage would be to use a transformer (lowers voltage) and bridge rectifier (converts, or "rectifies", the AC voltage to DC).

The main problem with this arrangement is that transformers operating at the 50Hz mains frequency are significantly less efficient than those operating at higher frequencies (in general, the efficiency of a transformer increases with frequency of input voltage). This is undesirable if the efficiency of the light is to be made as high as possible. Furthermore, the output produced by the bridge rectifier takes the form of *fluctuating direct current*, the exact pattern of which can be deduced by observing the graph of *y=abs(sin(x))*. This poses problems: the voltage will repeatedly fall to zero at 100Hz (once every half-wave), meaning that the LED will flicker visibly at a rate of 50-100Hz since the semiconductor chips have a very low thermal inertia. The problem is further exacerbated by the fact that the LED will generally only illuminate when the voltage of the *abs(sin(x))* input exceeds its minimum *threshold voltage*, thus further restricting the portion of the fluctuating input waveform for which it can illuminate and exacerbating the flicker.

To eliminate the poor efficiency of the transformer at 50Hz, a transistor-based oscillator can generally be employed at the first point in the circuit to significantly raise the input frequency to the transformer, thus reducing its requisite size by increasing its efficiency. After this, a bridge rectifier is placed across the output of the transformer with a capacitor in parallel with its output in order to create a *smooth* flow of truly direct current through the LED. This is the basis of a switched-mode power supply.

Dimming of LEDs can be accomplished by the use of special solid-state direct current dimming circuitry utilising pulse width modulation (PWM). This is a technique by which the LED is deliberately pulsed on and off very rapidly (typically hundreds of times per second in order to overcome the aforementioned lack of thermal inertia on the part of LEDs) such that the on:off ratio of the flickering is made proportional to desired intensity. This results in an apparently dimmer output level to the human eye which cannot perceive the individual pulses of the rapid flickering. In an LED fixture which can dim, the constant mains power enters the fixture and is rectified and lowered *before* it undergoes PWM and is finally output to the LED semiconductor emitter.

This circuitry used with LEDs renders them incompatible with existing theatrical dimming technology intended for conventional incandescent fixtures: the pulsed sine-wave produced by a phase angle control triac dimmer such as that discussed in H3.4 - *Phase Angle Semiconductor Lamp Dimmers* enters the fixture *before* the voltage rectification and lowering stage, thus interfering with the normal operation of the components such as transformers, transistors, and capacitors meaning that the lifespan of LED lights would be drastically shortened. Whilst there do exist LED lights which can derive power and PWM control from a triac-modulated mains supply, these are rare, expensive, unreliable, and do not offer particularly fine control of lower intensities. Ultimately, these factors mean that a total transition to LEDs would require extremely major replacement of control equipment (in order to accommodate fixtures with built-in PWM control as opposed to separate triac phase angle control dimmer packs) in a theatre, no doubt at great financial cost.

Furthermore, individual LEDs cannot be miniaturised into a very small area in the same way in which one may accomplish this with a tungsten filament lamp: the metal filament is a *point source* of light highly suited to use with reflectors and lenses. LED light cannot be focused in the same way thus reducing the potential of LEDs in replacing incandescent fixtures. Incandescent light is also excellent at rendering true colours because it is an almost perfect replication of sunlight. However, the same is not true for "white" LED light which is often distinctly tinted with blue. The consequences of this are twofold. First, the lighting provided by such lights, were they to be used exclusively, would likely be visually unimpressive. Second, the colours produced if a gel (colour filter) were placed in front of an LED fixture would not be true to those produced from the same gel in front of an incandescent fixture.

Useful Note:
An example of an LED light which can be controlled by a triac is a “dimmable” modern low-energy LED lamp for domestic lighting. This contains rectification, voltage lowering, and PWM stages which derive dimming from the triac-modulated power emanating from a wall-plate dimmer. These lamps typically dim with great unpredictability and tend to fail much more quickly than their non-dimmed counterparts.

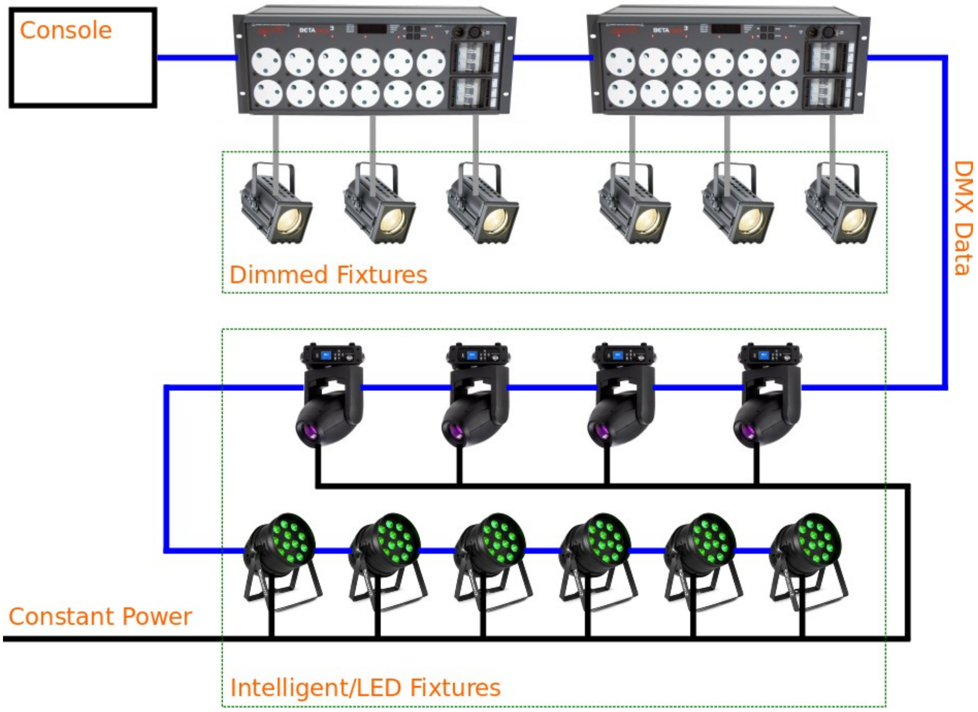
In spite of these problems regarding LED lights, they have certainly found use in the theatre industry. Unlike incandescent filaments, individual LED semiconductors are monochromatic (one colour) with regards to their light output. This means that if multiple sets of individual LED semiconductors (generally three: one red, one green, and one blue) are built into one fixture, by controlling the intensity of each set individually, any colour of light can be produced: the three primary optical colours are red, green, and blue. This renders LED fixtures useful for general variable coloured washes of light.

Since LED fixtures cannot be controlled by a conventional dimmed electricity supply, they are similar to the moving-head lights discussed earlier in that each fixture receives a source of ordinary, non-dimmed, mains power in conjunction with a direct connection to the DMX control daisy chain. This also allows for the fact that LED fixtures, as mentioned above with regards to the common use of three individually controlled sets of semiconductors, are multi-parameter devices: unlike a simply dimmed fixture (single-parameter device), each component colour can be individually controlled from the central console in order to change the overall light output colour of such a fixture.

Below is shown a typical LED fixture. LEDs are arranged behind circular plastic lenses. Most LED fixtures allow for the red, green, and blue components of their light output to be controlled individually:

Important Note:
LED lights (and indeed, moving-head lights) must *never* be connected to a source of dimmed power. This runs the risk of seriously damaging the fixture (and possibly the dimmer as well).

Below is shown a topological diagram of a theatrical lighting arrangement consisting of conventional dimmed fixtures, moving-head lights, and LED lights. The DMX line (blue) emerges from the console, loops through the dimmer packs but *not* through the dimmed fixtures themselves, through each moving-head light, and through each LED light. Whereas the dimmed fixtures receive dimmed power (grey line), the intelligent/LED fixtures receive constant power (black line):



LED fixtures also find use for ultraviolet (UV) lights. UV radiation lies just outside of the visible spectrum of colours and is not especially visible to the human eye. However, numerous materials exist which glow very visibly when UV light is shone upon them (indeed, this principle of *fluorescence* is what allows fluorescent tubes - discussed in H4.10 - *Gas Discharge Lights* - to produce useful light). This phenomenon is employed in theatrical aspects such as costume or set such that a particular person or item may appear unusually luminous if coated in such a UV-sensitive material and illuminated by a UV light.

Incandescent fixtures can be made to output any *visible* colour of light with the use of a simple filter owing to the fact that the white light produced by a glowing filament contains all the visible colours of the spectrum. Therefore, any individual colour can be "singled out" by the use of a filter. However, incandescent light has a negligible UV component which means that if a filter which "singled out" UV radiation were placed in front of an incandescent light source in the hope that UV light would be produced, essentially no ultraviolet radiation would emerge. However, since an LED may be manufactured to emit any wavelength of luminous radiation, specialist UV LEDs do exist. If these are mounted into a theatrical fixture such as that shown on the previous page, ultraviolet light may thus be produced.

Some sophisticated LED fixtures may contain not only red green and blue LEDs such that any colour of *visible* light may be produced, but also a separate set of UV LEDs such that ultraviolet light may be produced from the same fixture if necessary.

H4.10 - Gas Discharge Lights:

Gas discharge lamps are very commonly used outside of the theatre industry. They are a well-established form of electric lighting with a superior efficiency compared with incandescent lamps - the other main light source currently in widespread use.

The principle of gas discharge is that when an electric current is passed through a sealed vessel containing a gas vapour, provided the voltage is high enough, the vapour will glow. The glow from this gas discharge is seen as useful light. Examples of gas discharge lamps in common use include:

- Sodium lamps. These are used for street and outdoor security lighting. They are easy to identify owing to their distinctly yellow-coloured light output;
- Metal halide lamps. These are also used for street lighting and applications such as sport stadium lighting. Their light output has a blue-green tint;
- Fluorescent tubes. These are ubiquitous in any office/school. They are identifiable through their tendency to flicker when first energised, especially when starting in cold conditions.

Within the theatre industry, gas discharge lighting plays a somewhat less significant role with regards to stage lighting for two main reasons. First, as mentioned with regards to fluorescent tubes, discharge lamps take a considerable time period to "warm up" to their full level of light output. This is of inconvenience to theatrical applications which may require lights to be switched on and off quickly between scenes and is totally unsuitable for applications which require lights to be flashed or chased in rapid sequence. Second, gas discharge lamps will generally not work if an attempt is made to control them directly via conventional incandescent-orientated dimmer packs. Indeed, it is electrically difficult to lower the intensity of a gas discharge lamp at all, especially such that it dims down evenly and stably at very low intensities.

However, fluorescent tubes are frequently used in theatres, not as lighting during shows, but as work lights - those which are used during time periods for which a show is not running but during which rigging/preparation for a production is taking place. In these instances, there is no requirement for work lights to be dimmed and, since work lights are typically used for far greater time periods than show lights, the superior efficiency offered by the use of fluorescent tubes is highly desirable.

Some moving-head lights (discussed in H4.8 - *Moving-head Light* Fixtures) also utilise discharge lamps such as metal halide lamps for their light source instead of conventional incandescent lamps. High-power followspots may also use gas discharge lamps.

Fluorescent tubes also find use for emergency lighting in theatrical buildings. This type of lighting is particularly important for theatrical venues which typically contain very few windows. This means that, in the event of a fire or power cut, the venue must be equipped with adequate emergency (battery powered) lights to illuminate emergency exits and important obstacles/routes within the building. The enhanced efficiency of fluorescent tubes in comparison with incandescent lights makes them ideal for operating off a limited electricity supply from an emergency lighting battery. More modern emergency lights may also use LEDs - an even more efficient technology - as their light source.

H4.11 - Patching Theatre Lights:

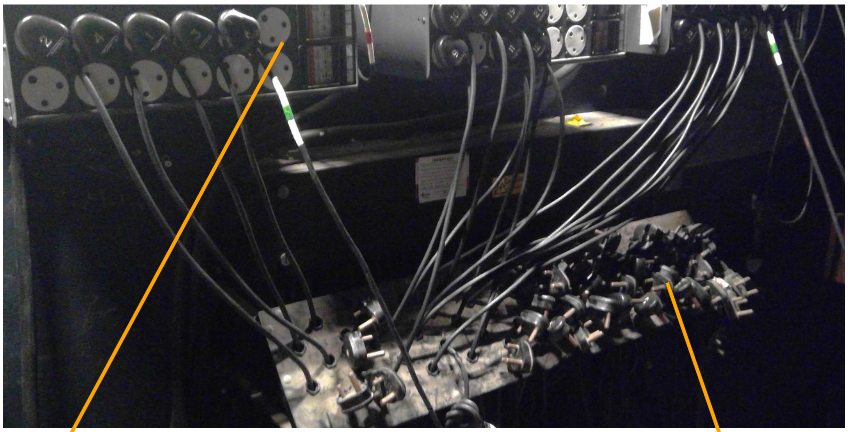
"Patching" a light refers to the process of connecting it to power and, in the case of an intelligent or LED fixture, DMX data, once it is suspended from a lighting bar. This process is generally accomplished by connecting the light to power through one of many socket outlets mounted on a properly constructed lighting bar. Each socket on a lighting bar is in turn linked to a source of dimmed or constant electrical power.

Below: a wall-mounted theatrical lighting bar. Note the way in which each fixture suspends from the bar using a metal clamp clip and connects to electrical power via a socket on the bar itself. The lights may be focused and directed at a desired part of the stage during the rigging/patching process:

In some venues, each lighting bar socket is hard-wired to a dimmer circuit. This means that, unlike the dimmer packs shown in H3.5 - *Theatrical Dimmer Packs* which have output socket connections, backstage dimmer packs are internally hard-wired to sets of sockets on lighting bars, with no need for the user to adjust any cabling between the dimmer packs and the lighting bar sockets; each socket along the lighting bar is always connected to one triac dimming circuit (see *Hardware 3: Lighting Dimmers*). Below is a dimmer pack (modified *Zero88 Betapack 3*) intended to have its 6 dimmed outputs brought out through hard-wired internal terminals as opposed to pairs of front-mounted sockets:

Another means of connecting bar sockets to power is by means of a switchboard-style *patch bay*. This means that, instead of each bar socket being permanently connected to a power source, it is simply brought out to a specific plug next to the backstage dimmer packs. These plugs can then be connected to dimmer packs with conventional front-facing outlets, thus providing power to the required bar sockets. This arrangement allows for the optional connection of certain bar-mounted sockets to sources of *constant* power if moving-head or LED fixtures are to be mounted instead of conventional dimmed incandescent fixtures. Furthermore, this arrangement also allows for greater versatility regarding which bar-mounted socket is connected to which dimmer channel. For example, if a certain channel of a dimmer pack fails, the light connected to it will cease to function. In a hard-wired state of affairs such as that discussed above, the only means of connecting the affected light fixture to a different, functional, channel is by ascending to the (possibly high) lighting bar and swapping the plug of the fixture into a different bar socket. This is assuming that spare sockets are even available along the bar. However, with the aforementioned telephone-style patching system, this problem can simply be resolved (at least temporarily) by moving the backstage plug corresponding to the bar-mounted socket into which the affected fixture is connected to a different, functional, dimmer channel without the need to make alterations at the level of the lighting bars themselves. Of course, it is still desirable to fix the faulty dimmer channel.

Below is shown a telephone-style patch bay using 15A round-pin plugs as a means of bar-socket-to-dimmer channel connection:



Spare channels on the dimmer packs allow for the easy transitioning of a fixture to a different dimmer channel (possibly even during a show) if a channel were to suffer a fault.

Each plug in the panel corresponds to an individual socket up on a lighting bar. This allows for greater versatility with regards to which dimmed channel controls which socket.

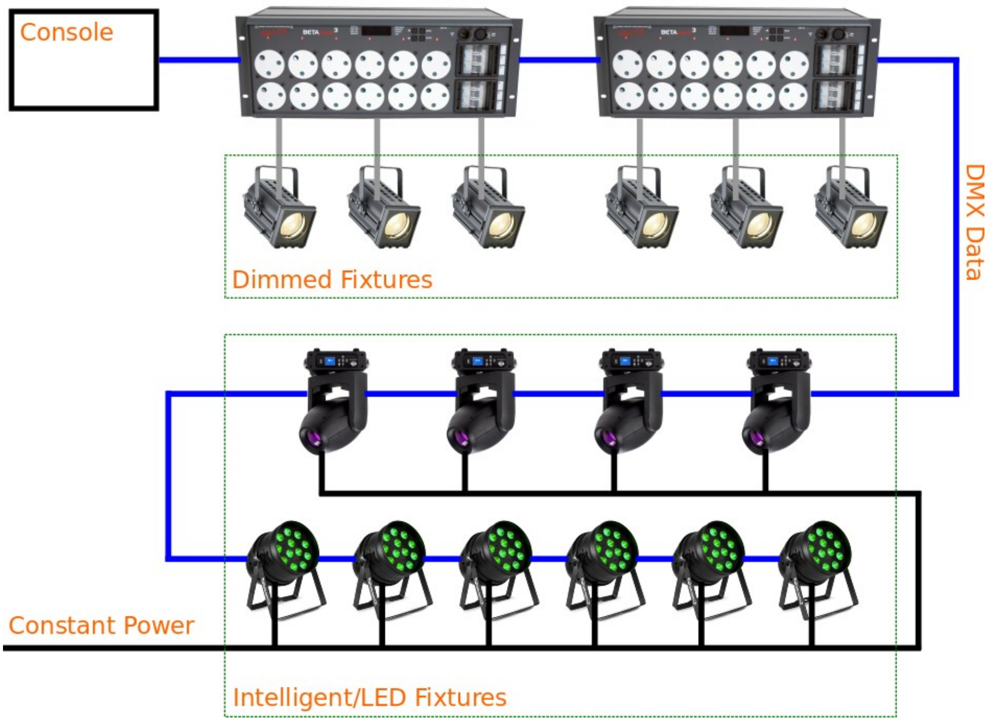
Some venues utilise CEEform or *Powercon* connectors both at the level of the lighting bars but also in the patch bay. Below is a modified *Zero88 Betapack 3* such that it outputs dimmed power over miniature CEEform sockets instead of the more conventional 15A round-pin sockets:

A further advantage of telephone-style patching systems, as mentioned briefly above, is that they allow for specific sockets up on the lighting bars to be connected to constant power, thus allowing for easy connection of intelligent or LED fixtures which are not run off dimmer packs, but contain their own voltage alteration circuitry as discussed in H4.9 - *LED Light Fixtures*. This connection can simply be accomplished by connecting the patch bay plug (corresponding to the desired bar-mounted socket) to a socket providing constant mains power. Typically, patch bays have a set of hard-wired round-pin sockets providing constant power alongside the dimmer packs in order to allow for this enhanced level of versatility.

If intelligent or LED fixtures are suspended on lighting bars, they will each also require connection to a source of DMX data to control their various different parameters. The most simple manner of accomplishing this is by looping a separate DMX cable emerging from the final dimmer pack along all the fixtures. Since DMX follows a daisy chain topology, the dimmer packs can be addressed and controlled independently of the intelligent fixtures. The presence of a daisy chain *does not mean* that all the fixtures along the chain act as "clones" of the incoming control signal and cannot each receive dedicated control. For more information regarding DMX control, see *Hardware 2: Introduction to DMX Control.*

It is important that the DMX daisy chain be addressed correctly in order to allow individual control of all intelligent fixtures and dimmer packs. For more detailed information regarding DMX addressing, see *Software 1: DMX Software Operation*.

The below diagram clearly shows the way in which a DMX data line (blue) from the main console may loop through the conventional dimmer packs and through intelligent/LED fixtures such that each fixture may receive dedicated control. Note the way in which the same data line as controls the dimmers is also capable of providing dedicated control to each intelligent fixture:



Hardware 5: Advanced DMX Devices

In spite of the fact that the DMX protocol is traditionally orientated around control of stage lighting, there exist many other theatrical devices which may also be controlled over DMX from the central lighting console. It is therefore important to have an understanding of the modes of operation of such devices. This section complements the earlier section, *Hardware 2: Introduction to DMX Control*.

H5.1 - Smoke, Fog, and Haze Machines:

Many productions often benefit from the presence of haze or smoke for enhanced atmospheric effects. A number of methods for creating theatrical smoke exist. The simplest way to create smoke is to burn combustible items. However, the smoke produced is unpredictable in volume/density and the heat from the combustion poses a major fire hazard.

An alternative and cheap method of creating smoke effects with significantly improved safety compared with simple combustion is by the sublimation of carbon dioxide. Carbon dioxide is quite a rare substance in that it changes directly from a solid phase (below -78.5 degrees Celsius) to a gas phase (above -78.5 degrees Celsius) with no intermediate liquid state. This process of *sublimation* means that if a solid block of carbon dioxide (popularly known as "dry ice") is melted by placing it in water at room temperature, a large quantity of thick foggy smoke is produced. As a bonus, this smoke does not cause eye or respiratory irritation. By altering the volume of dry ice allowed into the water per second, it is possible to adjust the density of the smoke produced to a desired level. Below is shown the smoke produced from the sublimation of dry ice upon immersion in water:

In practice, however, dry ice is somewhat impractical as a source of theatrical smoke not only because the solid dry ice will tend to melt when stored before use, but also owing to the fact that a dry ice smoke vessel cannot be controlled remotely as is desirable in a theatre: an operator must manually move the lumps of dry ice into the water as and when smoke is required. Furthermore, the smoke produced is tricky to direct outwards across a stage, often requiring external fans to accomplish this.

In light of these factors, one of the most common techniques for producing theatrical smoke is through the vaporisation of glycerol. This results in a similar smoke or haze which does not irritate one's eyes or airways. In addition, glycerol can be used to produce smoke from its liquid form, thus allowing for easier long term storage without the need for refrigeration.

Glycerol smoke machines contain a tank of glycerol fluid. This is pumped electrically through a heating chamber where it is vaporised to "smoke" which exits through the front of the machine. Some such machines - especially those intended to create overall "haze" as opposed to dense smoke - contain an electric fan in order to blow the smoke produced across the stage. This means that the machine itself can be placed in a wing space behind or beside the stage such that it is out of sight and still produces the required smoke.

Since the internal operation of a glycerol smoke machine is entirely electrical, it is easy to remotely operate the machine. This is accomplished over DMX; the pump and fan are addressed separately - each receives its own dedicated DMX control channel - such that the speed of each can be adjusted by a standard 0-255 binary-encoded multiplexed DMX signal. DMX smoke machines can be connected to an existing daisy chain of devices such as dimmer packs and/or intelligent fixtures.

Below is shown a glycerol haze machine (*Smoke Factory Tour Hazer*):

DMX control is received to activate the pump (to direct the glycerol through the heater) and fan (to blow the smoke across the stage).

Fan blows the haze out of the machine in order to spread the haze effect across the entire stage.

Diluted glycerol from a tank is pumped into an internal heater. Here, it is vaporised to a hazy smoke.

Useful Note:
The haze produced by glycerol machines is not considered hazardous to one's health: it is essentially water vapour such as that which emerges from a kettle.

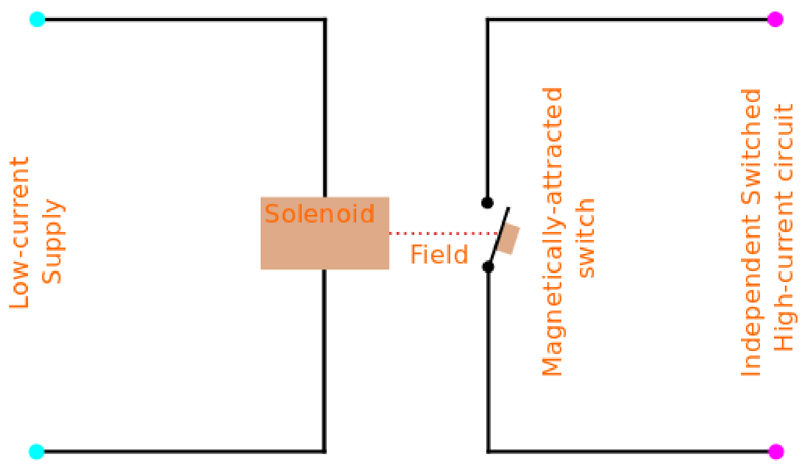
H5.2 - Remote Relay Switches:

An electrical relay switch is a very versatile device. It consists of a normal switch such as that used to operate simple room lights but with an important difference: the on/off action of the switch is actuated by remotely sending the relay switch an *independent* pulse of electric current. When the device receives this independent electric current, an electromagnet engages the two main switched contacts, thus completing the circuit through these primary contacts. When secondary power is removed from the relay, the electromagnet loses its magnetism and the switched terminals disengage.

This characteristic of relays renders them ideal for switching high-power electrical circuits from a separate low-power source: the current applied to the actuating coil may be very low, whereas the current through the switched terminals may be significantly higher.

One may recall from H3.4 - *Phase Angle Semiconductor Lamp Dimmers,* that a transistor is similar to a relay in that it regulates the flow of current through its two primary contacts based on a lower-current secondary input. However, semiconductors are very limited in their ability to switch high-power electrical loads. A triac - the vital semiconductor component in a phase angle light dimmer - represents essentially the upper limit of semiconductors in switching such loads. Electromechanical relay switches are excellent for switching high-power electrical devices between on and off states but, unlike a transistor, they are incapable of varying the current flow through their primary connections other than between an on state or an off state.

Below: an internal schematic of a relay switch. The solenoid coil is energised and therefore magnetised by the *independent* low-power side such that the switch for the high-power side may be magnetically operated by this remote low-current pulse of power:

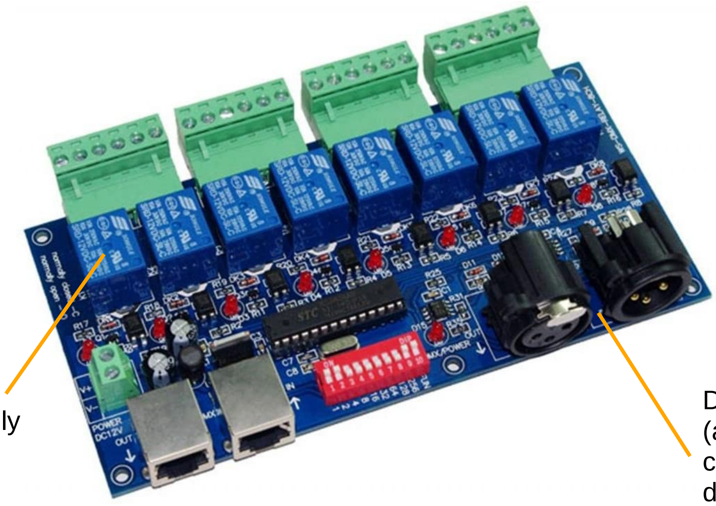


This diagram clearly highlights the fact that the low-current trigger circuit (that connected to the coil) is totally electrically isolated from the high-current side (that which is switched): the low-current circuit is an independent connection for the control of the switching of the high-current circuit. The coupling between the low-current control side and the high-current switched side is provided by the magnetic field established around the solenoid when it receives power. This field actuates the high-power switch.

Remote relay switches are useful in theatrical productions for switching electrical devices which cannot be connected to dimmer packs (excluding intelligent or LED lighting fixtures, which have internal DMX receivers and control gear). They allow for the switching of so-called "practicals" - physical lights which are *part of the set* such as a street lamp (on stage as part of a backdrop, for example) whose gas discharge mode of operation would render it unsuitable for receiving dimmed power. Similarly, sometimes it is desirable to use fans, positioned in the wings such that they bring about airflow on stage, to create controlled illusions of wind. Electric motors must also receive a source of switched, constant power and are therefore often controlled by such relays.

A typical remote-control relay for theatrical use receives a DMX input from the central lighting desk. Again, this DMX input may be daisy-chained to an entire universe of DMX devices likely already installed for console control. An internal DMX decoder receives a control signal from the console and uses this to activate the electromechanical relay, thus energising the connected device at the correct points in a show.

Below is a DMX relay module. It is common for theatrical devices such as these to be shipped as a standalone printed circuit board (PCB) for improved versatility when installing in a theatrical setting. This particular board has eight individually controllable relay switches (blue surface-mounted boxes):



H5.3 - Pyrotechnic Devices:

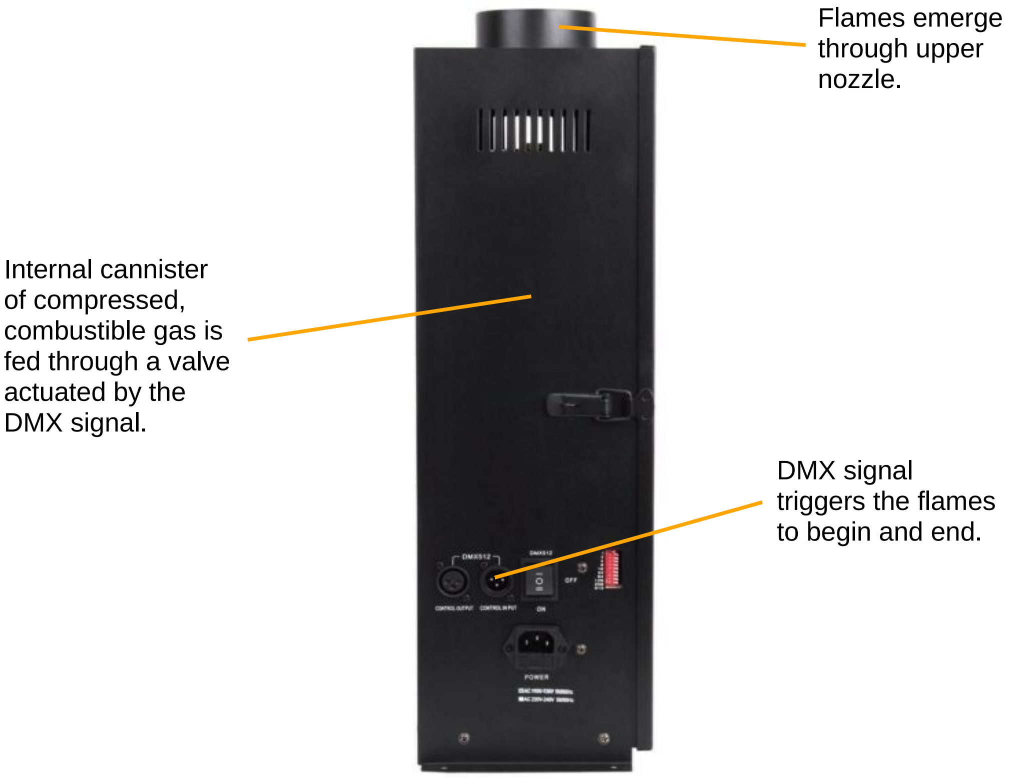
A pyrotechnic device refers to a machine which produces some kind of visible flame for use in a production. These are different to smoke machines in that the main reason for their use is not to produce smoke - in many cases, pyrotechnic machines use clean-burning fuels such as propane in order not to create undesirable indoor pollution - but to create large, vivid, yellow flames.

The inner workings of a pyrotechnic device are quite simple. An electronically controlled valve, opened and closed based on a DMX control signal, regulates the flow of butane/propane gas out of a pressurised cannister such as that used in a portable camping stove. When the signal is received for the valve to open, the propane/butane is allowed to emerge from the cannister. Now it is necessary to have some means of igniting the gas upon its first emerging from the cannister, otherwise it would fill the venue with dangerously inflammable vapour. This means of ignition is provided by a simple spark such as a spark plug from an internal combustion engine. This is triggered briefly, as soon as the valve opens, to initiate the combustion.

The output flame can be triggered and pulsed from the central console. Once again, the pyrotechnic device may be daisy-chained via DMX cabling in conjunction with other apparatus such as dimmer packs and intelligent fixtures.

Below is shown a set of theatrical pyrotechnic devices (flame throwers) in operation for the National Theatre's 2017 production of *Jane Eyre*:

Below: a DMX flame thrower device:



It is important to note that some pyrotechnic devices may not operate exclusively from a DMX control signal; they may require a secondary confirmatory trigger signal in order to avoid potentially unsafe false triggering. This secondary trigger is generally made by directly interrupting the internal electrical supply cable to the electronic valve on the gas cannister's output *independently to the DMX trigger control*. This wiring is then brought out to a secondary switch which may be operated by a "dead man's handle" located at the side of the stage - a device which only completes the circuit to the electronic valve once a second operator is continuously depressing two discrete buttons. Once this second operator is in place and pushing down the two buttons, the device may respond to the control signal emanating from the main control console. If the second operator notices a potentially unsafe situation, they can immediately remove one or both hands from the dead man's handle device and the pyrotechnic device will cease to function. Furthermore, since continuous pressure is required on *both* the buttons of the dead man's handle (typically one button for each hand of the second operator) for the circuit to be completed, the second operator cannot become distracted/fall asleep from monitoring the device and surrounding area of stage for dangers.

Concerning positioning of pyrotechnic devices, they are generally placed beneath small openings in the stage floor. Unlike smoke machines, they cannot be mounted above the stage on the fly floor such that the flame shoots downwards owing to the fact that flames will always tend to move upwards via convection.

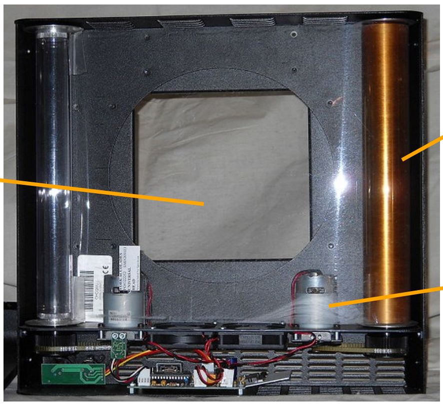
H5.4 - Colour Scrollers:

We have seen in H4.7 that the colour of light output from a theatre light may be altered by placing a coloured filter in front of the output. However, on conventional fixtures, this colour filter ("gel") can only be changed by climbing up to the lighting bars using a ladder, cherry picker, or scaffolding tower during the rigging process before a show may run. It is clearly highly impractical to attempt to manually change gels in this manner during a show.

In light of this problem, *colour scrollers* are sometimes used in theatrical productions to automatically change the colour of light emerging from an incandescent fixture. These are remotely operated from the main console. The layout of a colour scroller can be considered very similar to that of a cassette tape but with a very wide tape composed of gel material consisting of a row of consecutive differently coloured square light filters. This tape is wound onto two spools separated at such a distance that, at any time, only one coloured square on the tape may be made visible between these two spools. It is therefore the case that, by winding the tape backwards and forwards using the spools, different squares of colour can come into view. If this device is mounted onto the front of a light fixture, the light emerging from the fixture is filtered to a particular colour by the particular gel square presently in view on the scroller.

Electric motors are used to wind the scroll of consecutive colour filters backwards and forwards between the two spools in order that one light fixture may be used to produce a variety of different colours. Similar to intelligent or LED fixtures, scrollers require a source of constant electrical power and receive a dedicated DMX data connection such that the winding action of the spool motors may be controlled remotely.

Below is shown a photograph of a partially disassembled colour scroller. The two motors (visible as small silver cylinders, bottom left and bottom right) wind the spools in different directions such that any one of the filter squares present on the moveable filter film may be brought into view in front of the fixture, thus changing the emerging colour of light:



Colour scrollers lack the ability for so-called "live changes" to the colour of a light source. This means that the light fixture must be turned off before the scroller may be wound to a differently coloured section of tape since the winding process moves the boundary(ies) between multiple colour squares across the main aperture in order to reach the desired colour on the tape. If this winding were done with a full level of power applied to the light fixture, a highly visible "sweeping" of colours would be noticeable in the emerging light as the correct section of tape came into view - a generally undesirable characteristic.

H5.5 - DMX Buffers:

Ordinarily, a DMX universe consists of a linear topology of devices. This means all the controlled devices, be they dimmer packs or intelligent/LED fixtures, connect to each other in one simple daisy chain. However, there may be times when it becomes inconvenient to have DMX devices connected in such a manner. For example, it may be preferable, in order to minimise the transmission cable length, to split the cable in two very different directions, each heading to a completely different section of the venue. Since DMX data is multiplexed along the cable, every device would still receive individual control.

One may think that the aforementioned splitting of a cable may be achieved purely physically by splicing together two DMX data cables in a "Y" fashion such that the incoming data from the console splits into two branches, each heading to different parts of the venue (for example, one may head to the backstage dimer packs, whereas another may head to any intelligent fixtures on the lighting bars which require dedicated control). However, such a method of splitting DMX data frequently produces unreliable operation. This is owing to the fact that every time a split is made in the wire, the strength of the DMX data signal encoded on the wire decreases significantly. Therefore, this method is obviously unreliable if used in excess since it may cause the signal to fade to complete undetectability, thus rendering any attempted signalling useless.

As a result of the above problems, if a DMX data line must be split, a *DMX buffer* is used. This not only splits the incoming signal to many more "branches", but also *amplifies* the magnitude of the signal such that each "branch" still receives a signal of an adequate strength. DMX buffers typically input and output the data over the industry standard 5-pin XLR connectors such that any devices/cables may be connected.

Below is shown a basic DMX buffer. The incoming data is amplified and split to each of four sockets in order to eliminate the chance of undetectability. The cable emerging from each socket may be looped through sets of devices as usual. A DC input is also necessary in order to provide the additional signal amplification power:

DMX buffers also find use if unusually long runs of DMX cable need to be made (for example, between two buildings): one can place buffers at several points along such a long line in order to maintain the strength of the signal over such a distance where normally even the electrical resistance of the wire itself could cause signal degradation.

Important Note:
In spite of the fact that DMX buffers produce outputs to a set of multiple ports, each of which may be daisy-chained to a number of devices, they do *not* increase the number of universes present: the maximum total number of possible addresses remains at 512 as usual.

Software 1: Advanced Guide to DMX Software Operation

In *Hardware 2: Principles of Operation of DMX Control*, we explored the basic means of operation of the DMX signalling protocol now commonplace in the theatre industry. Having now an understanding of its main principles of operation and physical implementation, and having also explored some more advanced theatrical devices such as intelligent light fixtures and smoke/pyrotechnic machines, we can now proceed to discussing the exact signalling processes employed by the DMX512 protocol. It is important to grasp these since they outline the means by which one may correctly configure a DMX daisy chain (one "universe").

S1.1 - DMX Addressing of Dimmer Packs:

It was discussed, in *Hardware 2: principles of Operation of DMX Control*, how the DMX protocol allows for the dedicated control of up to 512 individual channels through only one cable. This is different to the earlier analogue standards which would require an individual wire for each channel of control (such as the multi-core analogue cables used on older dimmer packs to connect directly to fader potentiometers on a simple console).

As also mentioned in *Hardware 2*, the DMX protocol sends to each channel a binary-encoded number between 0 and 255. When controlling a fixture connected to a dimmer pack, 0 would correspond to 0% intensity (off) and 255 would correspond to 100% intensity (fully on), with any value between stipulating the proportional intensity of the dimmed light. The correct dimmer pack decodes the multiplexed DMX signal such that each of its channels changes to the correct percentage intensity based on the 0-255 signal on the control address corresponding to each channel.

Each channel of control outputted from the DMX console is assigned a unique address between 1 and 512. This address *is independent to* the actual numerical signal value (0-255) associated with that control channel: the address does not dictate the numerical 0-255 signal value - it simply serves as a transmission identifier. With the example of standard six-channel dimmer packs, the user selects which six addresses the dimmer pack should check, or "sample", from the data emanating from the console. Let us assume that the console is outputting the following data to the first eight DMX addresses:

Address	Numerical 0-255 Signal Data
1	134
2	255
3	0
4	234
5	214
6	213
7	177
8	143

If a dimmer pack connected to the tabulated DMX universe is set to sample the first six addresses for its channels of dimmer control. These dimming channels would be set to the following percentage levels (calculated based on the 0-255 signal proportion from above):

Dimmer Pack Channel	Sampled Address	Intensity/%
1	1	53
2	2	100
3	3	0
4	4	92
5	5	84
6	6	84

Important Note:
Do not mix up the terms "dimmer channels" and "DMX addresses". The former is specific to the dimmer itself and will never change based on DMX configuration whereas the latter refers to the classification of the multiplexed data emanating from the control console to certain dimmers.

Similarly, if the dimmer pack were set to sample DMX addresses 2 to 7 inclusive, its channels would be set at the following percentage intensities:

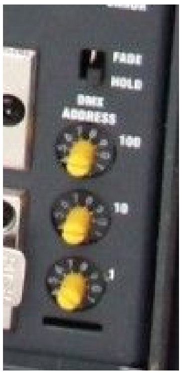
Dimmer Pack Channel	Sampled Address	Intensity/%
1	2	100
2	3	0
3	4	92
4	5	84
5	6	84
6	7	69

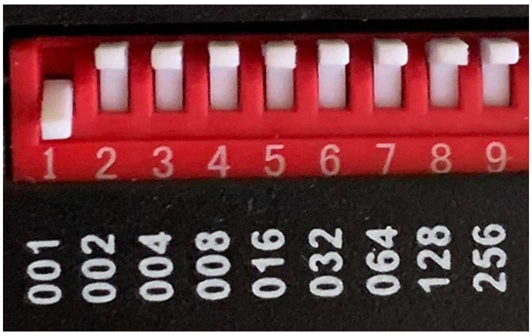
By daisy-chaining multiple dimmer packs, each set to sample a different address range, up to 512 channels of dimming can be controlled over a single DMX cable. As soon as a signal value on a particular address is changed by the console, the dimmer channel corresponding to that address adjusts in intensity accordingly. Most digital dimmer packs contain a small digital control module such as that annotated on the photograph of a *Zero88 Betapack 3* in H3.5 - *Theatrical Dimmer Packs*. This control module allows for one to set the *DMX start address* - the first DMX address sample point from which the dimmer pack will inclusively sample the data of six consecutive individual addresses for each of its six output levels. For example, if one sets the DMX start address as 7, the dimmer pack will sample DMX addresses 7 to 12 inclusive for its channels 1 to 6 respectively. Older DMX-enabled dimmer packs may use a component such as that shown below:

Here, the black up/down buttons above each digit allow for the mechanical selection of a three-digit number as the start address. By pushing the buttons, new digits mechanically come into view and the internal circuitry is reconnected for a different start address. These selector devices used to be more common on earlier DMX dimmer packs but have now been largely replaced by more robust, easy-to-operate, digital controls.

At this point, one must note that if the DMX start address on a dimmer pack is set to 512, it is likely that this will produce unpredictable incorrect operation because one DMX universe *only supports 512 addresses of control*; and a start address of 512 would mean that the dimmer pack would attempt to sample addresses 512 to 517 inclusive - a range with five non-existent addresses! Similarly, if any DMX device were set to sample non-existent DMX universe addresses, problems would result. On modern digital dimmer packs, the internal microcontroller may prevent the start address being set to a value nearer than 6 places away from 512. Older mechanical selectors, such as this one, however, may have no provision to detect this type of operator error and therefore rely solely on the knowledge of the user to set the address correctly.

Another two types of mechanical address selector are shown below. On the left selector, one sets the address using three rotary dials (one for units, one for tens, and one for hundreds). On the right selector, the address is set by inputting it in a *binary* fashion using one little white toggle for each binary digit (units, twos, fours, eights, etc.):





S1.2 - DMX Failure Modes:

It may be the case that a DMX network suffers a failure at some point whilst a production is in progress. Such failures typically result from a faulty connection anywhere along the daisy chain and can lead to the subsequent section of the daisy chain simply not receiving a signal. In this instance, it would be highly undesirable for all the lights or devices on this leg of the daisy chain simply to turn off as would typically be the case if a DMX dimmer pack were to stop receiving a data signal. It is therefore the case that many DMX devices (especially those with sophisticated digital interfaces, such as the *Zero88 Betapack* 3) are equipped with an automatic DMX *failure mode* in order to maintain some level of lighting even in the absence of an incoming DMX signal. Common failure modes are as follows:

- Preset sequence. On an intelligent or LED fixture, this makes the device carry out a repeated set of steps stored on its internal memory (not dependent on any sequence entering by means of DMX control). On a dimmer pack, this makes the attached lights chase in a specific, repeated sequence;
- Hold current state. The affected fixture(s) /dimmer(s) maintain the output state in which they were when they were last receiving DMX data;
- Fade to dark. Fixtures/Dimmer packs cease to produce an output, fading out over several seconds.

S1.3 - DMX Addressing of Moving-Head Fixtures:

Since moving-head light fixtures are becoming increasingly common and affordable, it is also the case that it is highly likely that one will need to configure such a fixture. It is therefore of importance to be acquainted with the exact means by which these fixtures are controlled over DMX.

Dimmer packs are inherently simple devices to control owing to the fact that each channel of dimming requires only one DMX address to control the intensity of the linked fixture. Intelligent moving-head fixtures, however, often have many more parameters which can be controlled from a compatible console. Such parameters include:

- Pan (side-to-side swivelling of the head);
- Tilt (upwards/downwards movement of the head);
- Colour filter (often accomplished by means of a built-in colour scroller; see H5.4 - *Colour Scrollers*);
- Light intensity;
- Gobo (a gobo swapper may allow for the automatic switching of gobo plates).

As a result of this plethora of controllable features, an individual intelligent fixture receives a *direct* DMX signal as part of the overall daisy chain (unlike simple dimmed fixtures, each of which receives a modulated power supply from separate banks of DMX-controlled dimmer packs). Furthermore, whereas each dimmed incandescent fixture on a simple dimmer-channel arrangement simply requires one 0-255 digital control address for its intensity, a *single intelligent fixture* occupies a series of consecutive DMX addresses, each one carrying a different 0-255 binary-encoded control signal to operate a different aspect of the fixture. More information on basic DMX addressing may be found earlier in this section.

> **Important Note:**
> Do not confuse the way in which dimmer packs and intelligent fixtures sample addresses. Whereas a dimmer pack generally samples a set of six consecutive DMX addresses, one for each incandescent channel of control, an *individual* intelligent fixture itself requires its own set of addresses.

It is possible to control a rotational parameter (pan/tilt) from a 0-255 address control signal. Such operation may be modelled thus (the "pan" parameter is used as an example here):

i) A common rotational unit of measure is the *degree* (^{o}). A full rotation consists of 360 degrees (360^{o});

ii) A single DMX address signal can take any discrete value from 0 to 255;

iii) Dividing the number of degrees in a full rotation by the maximum signal value gives $360/255 = 1.41^{o}$ for a single increment in the DMX signal;

iv) The fixture has a default "home rotational position" corresponding to 0 degrees and therefore also to an individual DMX address signal of 0;

v) Once the fixture receives a 0-255 DMX signal on its "pan" address, this numerical value can be considered to be multiplied by 1.41 (the number of degrees for a single DMX signal increment). The fixture then ensures that it is panned by this number of degrees from its home position.

Exactly the same procedure may be used for the "tilt" parameter, with the corresponding rotation simply happening on a different axis to that of the "pan" parameter.

The means of control for the "colour filter" parameter is somewhat different. The procedure is explained below for a fixture containing 17 different possible colour filters:

i) The DMX control signal on the address sampled by the fixture for its "filter" parameter may take any discrete value from 0 to 255 inclusive;

ii) The number of possible discrete DMX values for the "filter" address is divided by 17. This gives 256/17 = ~15 (decimal value is ignored since digital DMX signals *only ever take integer forms*);

iii) The above calculation means that each particular colour filter out of the possible 17 is "mapped" to a specific numerical range (one filter: 0-15; another filter: 16-30 etc.);

iv) The DMX control signal entering the fixture on its "filter" address is adjusted by the console. Depending upon in which range (certain numerical ranges correspond to certain filters) the 0-255 number from the console happens to fall, the fixture will adjust its colour filter to the corresponding colour.

The possible address input signal ranges and their corresponding possible colour filters are shown in the table below:

Signal Range	Corresponding Colour
0-15	Dark Red
16-30	Light Red
31-45	Yellow
46-60	Light Blue
61-75	Dark Blue
76-90	Light Orange
91-105	Dark Orange
106-120	Light Green
121-135	Dark Green
136-150	Dark Purple
151-165	Light Purple
166-180	Rose Tinted
181-195	Dark Rose
196-210	Grey
211-225	Warm Yellow
226-240	Lime Green
241-255	Clear

Useful Note:
Each colour has its own *range* of signals. This means that, if, for example, one observes the “dark red” row, it is the case that any value on the fixture’s “colour” address in the range 0-15 inclusive will result in the selection of the “dark red” filter.

This method of colour control is exactly the same as that utilised by a standalone colour scroller of the sort discussed in H5.4 - *Colour Scrollers*.

A similar process may be used for the "gobo" parameter. Also, this process may be adjusted for any number of filters or gobos; more filters will result in a smaller numerical signal range per filter whereas fewer filters will result in a greater numerical signal range per filter. The upper limit to the number of possible filters is 256 since only 256 discrete possible values may be taken by the 0-255 control signal on one particular DMX address.

Below is shown a table of these parameters along with their corresponding control addresses. This assumes that the fixture is set to sample DMX address 100 as the start address and that it will therefore sample addresses 100-105 for its parameter data:

Parameter	Sampled Parameter Address
Pan	100
Tilt	101
Colour filter	102
Light intensity	103
Gobo	104

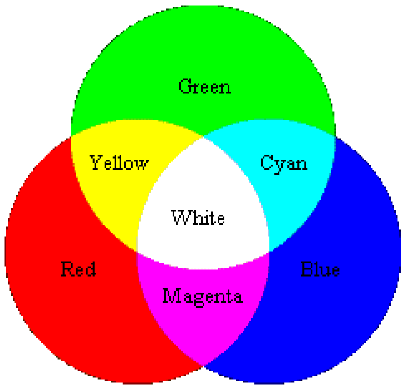
Each of these sampled DMX addresses of control carries a dedicated 0-255 control signal from the main console to operate a different aspect of the fixture's functionality. It would be a common arrangement to have, for example, a string of 3 moving lights set at start addresses 100, 105, and 110 (one for each fixture) such that each may receive dedicated control from a central console.

The start address of the fixture can be assigned using integrated controls similar to those used on DMX dimmer packs. It is very common to find a ubiquitous set of digital controls and display of the following kind on an intelligent fixture:

Using the M*enu, Up, Down,* and *Enter* buttons, one can adjust the DMX start address of the fixture in conjunction with a number of other user-adjustable settings. Such four buttons are common in some form on nearly all DMX-enabled fixtures and dimmer packs. Here is another such four button module as used on the *Zero88 Betapack 3.* From this, it is also possible to adjust the DMX failure mode (see S1.2 - *DMX Failure Modes*):

S1.4 - DMX Addressing of LED Fixtures:

Simple LED fixtures are typically stationary; they cannot be rotated/panned remotely but allow for the remote changing not only of light intensity but of output light colour. This aspect is achieved through the fact that white light is composed of the three optical *primary colours*: red, green, and blue. By adjusting the respective intensities of three specific overlapping light sources of these colours, *any colour* of net light output from the visible spectrum may be obtained. Below is shown a useful "overlap diagram" of the three primary colours of light. The three primary circles overlap, giving some examples of the possible colours which may emerge from this mixing process:



An incandescent lamp inherently produces white light: its spectral distribution of constituent colours is even and can therefore be considered to consist of roughly identical proportions of the three primary colours. A filter can be used to restrict the spectral distribution of the light output to a more narrow range of wavelengths (colours of light).

An individual LED, on the other hand, can only produce monochromatic light - that of a single colour. It is therefore the case that LED theatrical fixtures must contain three sets of LEDs, one for each luminous primary colour. Most LED fixtures allow for each primary colour emerging from the fixture to be adjusted individually such that any output colour may result. For example, if white light is desired, the ratio of red:green:blue is set to 1:1:1. However, if pure blue light is desired, this ratio may be adjusted to 0:0:1. More complex ratios may be achieved by adjusting the individual intensities via a DMX control signal from the main console.

An LED fixture contains multiple groups of three primary LEDs clustered in trios behind many small round lenses on the front of the fixture to provide some level of directionality. The red, blue, and green groups behind the lenses are controllable individually.

Below is shown a common LED fixture:

Constant power and DMX data connect to the rear of the fixture.

Three LED chips (one red, one green, one blue) are located behind each plastic lens. The red, green, and blue sets are controllable individually.

A fixture such as this typically occupies 3 consecutive DMX addresses of control: one for the red component, one for the green component, and one for the blue component. By sending three 0-255 values over these addresses, the colour (and intensity) of overall light output may be altered. For example, if the three addresses (red:green:blue) are carrying the control signals 255:255:255, the output will be white. A lower-intensity white output may be obtained by setting the address signals to 50:50:50. This maintains the same red:green:blue ratio but with an overall lower output level.

Just as with a conventional incandescent fixture, the percentage intensity of each component may be calculated easily by observing the numerical proportion of 255 reached by each component's input signal.

It was mentioned at the start of this section that LED fixtures are typically stationary. However, moving-head LED "wash" fixtures are gaining popularity. Whereas conventional moving-head fixtures typically operate using incandescent or gas discharge lamps (usually in a sealed body), moving-head "wash" lights use the above characteristic layout of LEDs behind lenses such that a somewhat directional wash of light may be produced whose colour and direction may be remotely adjusted.

Below is shown a moving-head LED wash light. It may be clearly seen to be a hybrid of the LED fixture on the previous page and a traditional moving-head light:

Concerning the DMX addressing of such moving-head LED fixtures, the number of addresses occupied for controlling each aspect of the fixture will obviously be larger than for a simple LED fixture since the pan and tilt parameters may also be controlled. However, whereas it was mentioned in H4.8 - *Moving-Head Light Fixtures* that a parameter may also correspond to a colour filter, such would not be the case in an LED wash light such as this owing to the ability to control the exact red, green, and blue components of light as discussed above, thus achieving any desired output colour by this means instead.

Below is a table showing the parameters controllable on a simple moving-head LED wash light starting on DMX address 100:

DMX Address	Parameter
100	Intensity (red component)
101	Intensity (green component)
102	Intensity (blue component)
103	Pan
104	Tilt

Observing this table, one will notice that there is no "gobo" parameter. Such is very common for LED fixtures owing to the inability of LED light to be specifically focussed - an aspect which is essential if a gobo is to be used. Therefore, if a gobo were used, the silhouette produced would be blurry at best, and most likely unrecognisable. Instead, the light emerges directly through the round translucent plastic lenses visible on the front of the fixture's head.

S1.5 - DMX Addressing of Relay Modules:

Relay modules are not capable of providing dimmed power to the devices under their control but instead simply switch on and off power to their devices. This means that a variable 0-255 incoming control signal on the particular DMX address corresponding to a relay has to be interpreted such that it turns the relay on and off in a binary fashion. The simplest and most common interpretation of an incoming signal for simple relay switches is as follows:

i) 255 (the maximum number possible on a DMX control address) is divided by two and the result rounded to the nearest integer. This forms a "cut-off" point. The result in this case is 127;

ii) If the incoming signal is below 127, the relay switches off;

iii) If the incoming signal is above or equal to 127, the relay switches on.

The result of this manner of interpreting the incoming numerical data is that a simple binary switching action may be achieved - exactly as is desirable for the relay. The exact numerical "cut-off" point between the relay being on and off may vary between different devices but generally lies around the halfway point of the possible set of numerical input values.

In H5.2 - *Remote Relay Switches*, an example was given of a module with 8 individually controllable relays. Such a module would therefore sample eight consecutive DMX addresses, interpreting the numerical value taken by each address signal based on its "cut-off" point.

S1.6 - A DMX Universe:

It has been established that an entire chain of DMX devices is termed a "universe". The maximum number of individual controllable addresses available on a DMX universe is 512. Typically, these addresses are split between dimmer packs (for the majority of the lighting fixtures), advanced devices such as smoke machines or relay modules, and intelligent fixtures. Now each intelligent/LED fixture occupies considerably more addresses than a simple dimmed fixture in order to control its many parameters. Whereas a six-channel dimmer pack, sampling six consecutive addresses, may control six individual fixtures, an intelligent fixture may occupy six addresses *itself*.

A table showing an example distribution of DMX addresses in a small set of theatrical fixtures is shown below. The dimmer packs have their own range of addresses whereas the moving-head lights occupy different ranges. The absence of overlap between any of the devices' address ranges means that *each device may receive dedicated control* from the central console:

DMX Address	Parameter	Device
1	Channel 1	Dimmer pack 1
2	Channel 2	
3	Channel 3	
4	Channel 4	
5	Channel 5	
6	Channel 6	
7	Channel 1	Dimmer pack 2
8	Channel 2	
9	Channel 3	
10	Channel 4	
11	Channel 5	
12	Channel 6	
13	Pan	Moving-head light
14	Tilt	
15	Colour filter	
16	Light intensity	
17	Gobo	
18	Intensity (red)	LED light 1
19	Intensity (green)	
20	Intensity (blue)	
21	Intensity (red)	LED light 2
22	Intensity (green)	
23	Intensity (blue)	

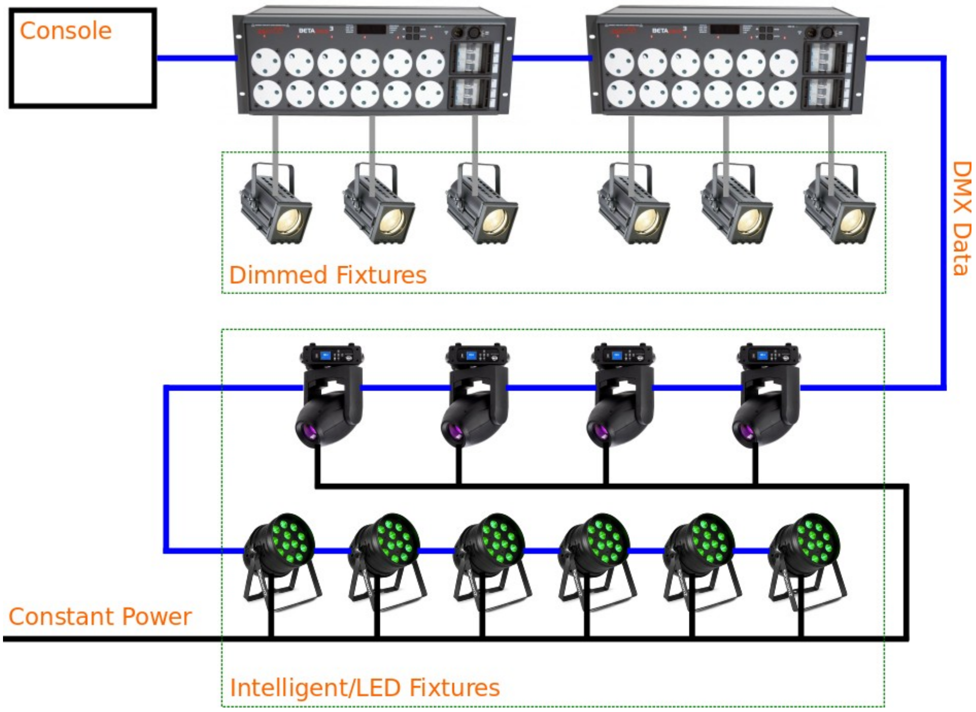
Useful Note:
This arrangement only occupies 23 of the 512 possible DMX addresses available for one universe. More intelligent fixtures or dimmer packs will increase this number of occupied channels.

It may also be the case that different DMX devices are set to sample the data from the same address range. For example, if dimmer pack 2 were set to the same range as dimmer pack 1 – addresses 1 to 6 inclusive – then increasing the DMX signal on address 1 would bring up not only channel 1 of dimmer pack 1, but also channel 1 of dimmer pack 2. In this way, many more devices may be connected to the same 512 addresses of control.

S1.7 - Limitations of DMX Control:

The DMX512 data transmission protocol has become an incredibly popular universal standard for control of theatrical devices to the extent that traditional analogue dimmer packs are now essentially obsolete. It is also used in venues such as concert/disco halls in order to provide easy control of lighting effects. However, in spite of its advantages in allowing for the creation of an easily controllable daisy chain of devices over a single cable, it also has a number of drawbacks, not least in terms of the potential for failure, often within the cable itself.

Consider the following DMX universe:



If the DMX data line (blue) were to become broken between the dimmer pack and the first moving-head light, the daisy chain topology means that control would be lost over all the moving-head (middle) and LED (bottom) fixtures. Unfortunately, the potential for breakages in DMX cabling is somewhat large. The main point of breakage is the XLR plug itself: if the cable is pulled hard or strained during the rigging process, the soldered connections inside the plug may pull apart. However, the cabling itself may also become damaged owing to improper handling. Similarly, DMX cabling hard-wired into a venue (for example, embedded within the walls in order to lead discretely from the auditorium console to the backstage dimming equipment) may become damaged during building work. If the damage is subtle, pinpointing the point of breakage along the cable will be a tedious task.

Furthermore, often following physical abuse or wear, DMX data cables may develop internal short-circuits. This means that the cables or plugs themselves start conducting internally at points which should normally be electrically insulated from each other with the result that a cable itself may start producing its own bogus control "data signals" - signals which should normally emanate exclusively from the main console in order to operate the universe's fixtures. The result of such a fault often manifests itself through entirely random flickering/triggering of fixtures. This is of great inconvenience if such a fault occurs during a show but may be dangerous if devices such as pyrotechnic flame throwers are connected to the daisy chain because they could trigger unpredictably and uncontrollably.

A further disadvantage of DMX control manifests itself through the consequences of a failure of a single device on the daisy chain such that its DMX connectors become live at a dangerously high voltage. Since, under normal operation, digitally encoded DMX control signals only operate on ~5v, the application of 240v mains power onto the DMX daisy chain by a faulty device would have the potential to cause major damage to *every device* on its daisy chain, not to mention the risk of electric shock to anyone touching exposed conductive parts of the DMX cabling/connectors. In order to minimise the likelihood of this occurrence, DMX-enabled devices typically have their internal DMX circuitry very well isolated from any high-voltage components in order to minimise the chance of any sort of dangerous voltage finding its way onto the DMX data line.

It is also the case that it is not only faulty devices which may put dangerously high voltages onto a DMX data line. The non-compliant smoke machines discussed in H2.3 - *Physical DMX Connectors* also have the potential to cause damage to entire sets of DMX devices if erroneously connected to a DMX universe.

When an electric current flows through any conductor, there is some level of electrical resistance in the conductor itself to the flow of electrons. This means that the energy carried by an electric current will "fade" (reduce in magnitude) by a certain level as it travels along even a simple wire. Since DMX signals utilise low voltages, it is the case that if a daisy chain of very many devices is made, the signal may fade to undetectability owing to the electrical resistance of the connecting wires and the devices themselves. The general rule of thumb is that no more than **32** physical devices should be connected along one DMX daisy chain, regardless of the way in which they are addressed. This could be 32 dimmer packs, 32 intelligent fixtures, or a combination of both. This figure is, however, not definite; in many applications, running more than 32 physical DMX devices along one daisy chain may turn out to work perfectly.

Ordinarily, a DMX universe will contain a linear topology of devices daisy-chained straightforwardly off each other. In the case of a venue based entirely around conventional dimmed fixtures, it is highly unlikely that more than 32 dimmer packs (each dimmer pack is one DMX *device*, even though it occupies six consecutive *addresses* for six fixtures) would be required and the aforementioned rule will not be an issue. However, if many fixtures such as moving-head or LED lights are to be used, it may indeed become the case that the number of devices on a leg of the network exceeds 32. Such a problem may be mitigated by using a DMX buffer (see H5.5 - *DMX buffers*). Since such devices produce multiple sets of re-amplified signals, this means that up to 32 devices may be connected linearly to *each output port* of the buffer (provided the overall number of required addresses does not exceed 512).

Useful Note:
If the total number of addresses spanned by all the fixtures/devices on the DMX universe is greater than 512, certain devices may be made to overlap address ranges such that, for example, an entire row of LED fixtures all operate off addresses 101-103. This provides control over the entire row but not over each individual fixture.

It has been shown in the section prior to this one that intelligent fixtures occupy significantly more DMX addresses of control than traditional dimmed fixtures, each of which only occupies a single control address - that corresponding to light intensity. The result of this requirement for very many addresses of control on the part of individual intelligent fixtures means that very large venues with many dimmer packs for incandescent fixtures and a multitude of intelligent fixtures, each requiring their own dedicated control address range, may face a shortage of available DMX addresses: the number of addresses required by all the DMX devices in the venue may exceed 512. Now since 512 is the absolute maximum number of control addresses available on a single DMX universe, some venues may contain two DMX universes, thus doubling the number of available control addresses. Of course, two individual universes of control require a specialised control console which can produce not only one DMX output over a single XLR connector for one universe, but *two* DMX outputs (one to each universe), each over a separate XLR connector. A popular multi-universe arrangement consists of the dimmer packs all connected to a first universe and the intelligent/LED fixtures connected to a second universe.

For extremely large, possibly outdoor or stadium-sized events, it may be the case that the total number of fixtures would necessitate even more than two DMX universes for complete control. Whilst it would, theoretically, be possible to operate any sufficiently large number of DMX universes, provided a console with an adequate number of output connections were used, the rigging and patching process would be made significantly more complicated by the presence of multiple data lines emerging from the console (one for each universe). Furthermore, owing to the aforementioned difficulty of finding faults on even a single DMX universe, troubleshooting on such a complex multi-universe network would be essentially impossible. As a result of these inconveniences, there now exist numerous more advanced (albeit rarer) control protocols which can carry many times more control data than a simple DMX universe over a single cable.

Typical cables used for such standards as the above are often CAT5/CAT5e Ethernet cables popular in IT for networking computers together in corporate buildings. In such an arrangement, a special console distributes multi-universe control data through an Ethernet cable. Special decoder boxes connect along various points of this cable in order to "break it out" to multiple conventional DMX signalling universes *in the exact regions of the venue where they are required,* instead of running very many DMX lines from the console to every part of the venue. For example, decoder boxes may be placed by the dimmer packs and above sets of lighting bars such that the length of actual traditional DMX cabling required is minimised. The exact method(s) of data transmission of such sophisticated alternatives to DMX transmission are significantly more complex than the comparatively simple multiplexed data sent by the DMX512 protocol. Such methods are often orientated around the IT-standard TCP/IP protocols; their exact modes of operation are beyond the scope of this guide.

Software 2: Operating a Lighting Console

As has already been established in previous sections, ultimate control of theatrical lights and other DMX devices rests with the central control console. It is therefore the case that knowledge of the principles of operation of such consoles is essential.

In spite of the fact that this chapter is part of the *Software* section of the guide, it is not necessarily the case that all lighting consoles are digital. Certainly, it is now commonplace for theatres to operate using a fully computerised lighting console which can easily create the multiplexed data necessary for a DMX universe, but older consoles intended for use with analogue (non-DMX) dimmer packs such as those discussed in the former half of the *Hardware 3: Lighting Dimmers* chapter are often simply a set of potentiometers linked back to triac dimmer circuits, often with little or no active electronics present in the console itself; a console of this sort simply exists such that the potentiometer faders are all grouped together in one place to offer convenient and compact control of all the channels of dimming. Analogue consoles typically have no provision for controlling any advanced devices such as those discussed in *Hardware 5: Advanced DMX Devices* and are intended to be used exclusively with simple dimmed incandescent lights.

S2.1 - The most Basic Type of Console:

The most basic type of lighting controller simply consists of a row of faders. In such a basic arrangement, each fader controls one dimmed channel on the backstage dimmer pack. By moving a fader up or down, the intensity of a particular channel (fixture) may be raised or lowered. Below is shown a six-channel DMX controller of this kind:

In this picture, one will notice the extra rightmost "master" fader. This is similar to the "master volume" on a stereo and allows for the overall control of the intensity of all channels simultaneously. For example, one may set each left-hand fader to a desired level and then adjust the overall intensity of all channels up or down using the master control.

These consoles are limited for control of show lighting owing to their inability to store any preset "scenes" - sets of pre-stored lighting levels - which may be changed by the push of a single button or fader. Instead, the intensity has to be controlled "live" by adjusting each individual fader as and when changes are required. Such controllers are, however, occasionally used in place of conventional room light switches in venues where it is desirable to dim the standard room lighting or to control various sections of the room's lights individually. The room lights are then dimmed by separate standard theatrical dimmer packs positioned in a discrete location.

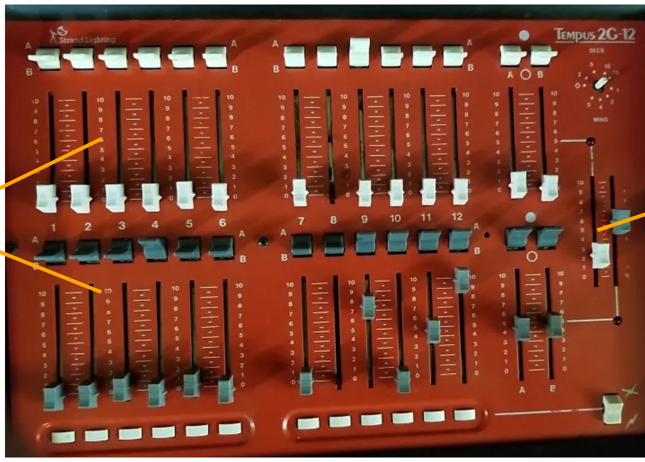
S2.2 - Preset Consoles:

Preset consoles, the next step up from those described in the previous section, offer the ability for two separate scenes of lighting to be set up on two different banks of faders. A "crossfade" between the scenes may be made by using a separate fader, similar to a master.

The major advantage of preset consoles is that they allow for the "storage" of a lighting scene *other than that which is currently active*. These consoles typically have two rows of faders, one for the first available scene and another for the second scene. An operator can set up a scene on one row of faders which is output live to a set of dimmed channels. However, *whilst this scene is live*, another scene for *the same range of channels* may be set up on the second row of faders. This second scene is not output live until the main crossfade fader is slid to its opposite end of travel such that the original scene fades out and the new scene fades in. Once the new scene from the second fader row is live, the original row of faders may be set to the levels for a third scene. The master crossfade fader may then be readjusted such that the first row once again becomes live and the second row may be edited for the next scene. This process can be repeated infinitely.

Below is shown a preset console (analogue *Tempus* desk from *Strand Electric*) such as that described in the above paragraph:

Two rows of sliders operate the same range of channels. One row is live, and the other is the “stored” next set of levels.



Master crossfade slider(s) allow for the smooth transition between the live scene from one row of sliders to another from the other row.

Preset consoles are vastly superior to the most basic controllers discussed in the section prior to this one. However, they still rely on adjusting faders during a show: while one scene is live, the operator is inputting the levels for the next scene into the alternative row of faders. This reliance on the live adjustment of faders makes simple preset consoles such as the above *Strand Tempus* console unsuitable for very rapid bursts of scene changing since such changes would not allow the operator the necessary interim period to set the levels for the next scene, even though the actual crossfade itself is only governed by a single fader, or pair thereof.

As a result of the above issues with preset consoles - most of which are not greatly computerised, other than the inclusion of a DMX XLR communications port on more modern types - there exist further improved consoles which allow for the digital storage of an essentially infinite number of pre-programmed lighting scenes, each of which may then be recalled by the push of a button, with no need to adjust any faders at all during a show.

S2.3 - Cue Storage Consoles:

Cue storage consoles are computerised to the degree that they can store a great many individual scenes of lighting in solid-state memory. These scenes can then be recalled and output to a DMX (or, in rare cases, analogue) universe of control as and when they are required simply by pushing a cue button. Many storage control desks, such as the *Zero88 Alcora* or *Jester* also have a set of conventional faders for the initial programming of lighting scenes, or "cues", during technical rehearsal periods.

In the programming mode of operation, scenes are inputted to the faders on the console or set via a digital keypad/keyboard and then stored to the console's internal memory such that they can then be recalled *without adjusting any faders* during a show. In the playback mode of operation, the individual scene cues can then be selected and made live by simply pushing a cue key.

Digital storage consoles often have a number of additional features compared with simple preset consoles:

- A computer monitor can be attached to a display connector on the back of the console in order to see a tabulated list of all stored scenes. This is of great use during a show when scenes are being played back from the console's memory;
- A computer keyboard may be connected in order to type in cue names for each lighting scene. This helps to identify the correct scene to which a transition is required during a show;
- Specific fade times may be programmed in order to ensure even and visually pleasing transitions between different lighting scenes;
- So-called "chase" memories may be programmed. These allow for the rapid-fire flashing of lights which would be very hard to achieve with a simple preset console;
- A USB port or floppy disk drive may allow for a set of stored scenes to be saved to an external memory device.

Below is shown a common digital storage console (*Zero88 Jester*):

S2.4 - Console Control of Advanced DMX Devices:

Lighting consoles which operate over DMX are also used to control numerous advanced devices other than simple single-parameter dimmed fixtures. Examples of such advanced devices include moving-head lights, LED lights, colour scrollers, and smoke machines.

Even if a basic DMX console is intended to exclusively control simple dimmed fixtures, it is often possible to use its output signals to control other devices as well. For example, a console may be configured such that three of its dimmer faders are DMX-addressed to the three parameters of an LED fixture - red, green, and blue - instead of the intended conventional dimmer channels. Thus, by altering the level of each of these three faders, any output colour may be achieved from the corresponding LED fixture: each fader simply outputs a 0-255 DMX signal on a particular address which is universally recognisable by any DMX-enabled device. In this way, it is often possible to control many different sorts of DMX devices from a standard console.

A further example would be a remote relay module. As discussed in S1.5 - *DMX Addressing of Relay Modules*, the numerical DMX input for the address corresponding to the relay is divided into two equal ranges such that if the signal is in one range the relay switches on; if it is in the other, it switches off. If a desk fader were mapped to a relay, the response point at which the relay switches on/off would be located at the centre of the fader's travel such that the fader can act as a switch of sorts.

However, moving-head lights may present problems when operated exclusively from faders. This is owing to the fact that they utilise "pan" and "tilt" parameters in conjunction with simple intensity, colour, or speed control such as would be the case for other DMX devices (e.g. colour scrollers and smoke machines). Certainly, a moving-head light's pan/tilt could be controlled from a pair of faders, each outputting a 0-255 signal for the different pan and tilt addresses of the fixture as discussed in S1.3 - *DMX Addressing of Moving-Head Fixtures.* However, such control may prove unintuitive owing to the use of a linear fader to control a rotational parameter. It is therefore preferable, if large numbers of moving-head lights are to be controlled, to utilise a console with dedicated *encoder wheels*. These are rotary knobs whose rotation corresponds to that of the pan/tilt of the fixture being programmed. Typically, these wheels may be used to program the movement of a moving-head light into a digital console's internal storage such that the movement may be replayed during a show through the transmission of a sequence of adequate DMX signals stored in the console's memory.

Below is a close-up photograph of a set of rotary encoder wheels on a console intended to control moving-head lights (*Zero88 Solution*). These are used during the programming process to load movements which will be replayed during a show as part of scenes:

S2.5 - Professional Consoles:

The consoles discussed so far are largely the varieties which are most common in venues such as small theatres or school/village halls. However, professional environments often demand a greatly superior level of control and therefore utilise even more sophisticated control consoles to those discussed thus far.

Such advanced consoles are typically not orientated around fader control. Instead, a numerical keypad can be used to input percentage intensities to specific ranges of DMX dimmer addresses. Encoder wheels are included to program moving-head lights as well. Furthermore, the internal workings of such a console closely resemble those of a desktop computer, containing items such as a full PC motherboard and hard drive in order to allow for efficient computerised operation. The presence of a hard drive also allows for the storage of many cue lists for *many different productions* simultaneously. This is of great use to large venues which may have multiple different shows running concurrently at different times of day.

The presence of a high capacity hard drive in such consoles allows for the internal storage of a database of all common DMX devices from common manufacturers and their specifications. This is of great use when configuring the lighting equipment for a show since complex multi-parameter devices may be addressed and configured for desk control simply by recalling the database record corresponding to a particular fixture; this loads the necessary DMX parameters directly into the show file and rehearsal programming can then begin immediately. This is instead of manually configuring each address of control for each different parameter of the fixture as would be the case with more basic consoles. The database may periodically be updated to account for the release of new fixtures by way of firmware updates, issued by the console manufacturer.

DMX device databases also allow for the precise control of devices such as colour-variable LED lights. Whereas when controlled from a more basic DMX console, each of the three optical primary colours is varied by a crude fader (see S1.4 - *DMX Addressing of LED Fixtures*), a professional console may include an on-screen "colour picker" similar to those used for computer graphics software packages. By selecting colours from this picker using a keyboard/mouse connected to the console, the necessary DMX values for each primary optical colour corresponding to the overall selected colour are automatically encoded and sent directly to the fixture with the result that the fixture instantly switches to the selected colour with no need for the tricky adjustment of multiple faders. This makes the live adjustment of colours during a show (without pre-programmed cues) much easier.

Since it is becoming increasingly rare for large theatrical venues to operate exclusively from incandescent dimmed fixtures, it is the case that almost all modern consoles intended for professional theatrical use include ample provision, such as encoder wheels and the aforementioned colour picking techniques, for the control of intelligent light fixtures as well as that of standard dimmer packs and their corresponding incandescent lights. Consoles intended for larger venues where the use of a single DMX universe may impose restrictions on the maximum number of possible fixtures often include two DMX output ports such that two independent universes may receive control from a single console, thus doubling the maximum number of possible DMX control addresses.