While today’s hydraulic systems are highly sophisticated, they are based on relatively simple devices operating on a few easily understood principles. In its simplest form, a hydraulic system consists of a pump driven by an external power source that uses pistons, vanes or gears to pressurise a fluid and move it through the system in paths determined by valves to power cylinders, motors, and other devices that transform the flow of pressurised fluid into motion to do useful work.

In lift-trucks and ground support equipment, that useful work typically includes manipulating a mast or other load-handling device, steering the vehicle and, in many cases, providing the energy to propel it as well. Each of these functions, in turn, depends on precise control of the flow of hydraulic fluid within the system, and that control is provided almost entirely by the valves.

While the operating principles of pumps, motors and cylinders are intuitively understood, valves tend to be more mysterious. In reality however they are no more difficult to understand than other system components. Valves may be broadly categorised by function. They either control flow rate, pressure, direction, or some combination of these attributes. Flow- and pressure-control valves are generally based on metering the fluid through an orifice or other restriction at an adjustable rate. A simple needle valve is a good example of this technology, although in today’s systems the control capabilities are much more sophisticated.

Directional-control valves are used to control the path the fluid takes through the system. Raising and lowering the mast or forks of a lift-truck, for example, is controlled by a directional valve, as are virtually all other motions produced by the system. Even steering-control units are basically rotary directional-control valves.

At the most fundamental level, there are two typical forms of directional valves – those that control the flow of the fluid by moving a spool within a bore to selectively connect different ports, and those that control the flow with a poppet or poppets. Directional valves are also distinguished by the way in which the control element is actuated, with the most common options being manual, hydraulic and electric.

**Spool-type valves**
In a spool-type valve, fluid is routed from the external ports through the valve body to cavities or openings in the wall of a central bore. The simplest configuration is a two-port valve having only an inlet and an outlet. A cylindrical, linearly movable spool within the bore controls flow from the inlet to the outlet.

The simplest spool has a groove, or metering notch, machined into its diameter that is of sufficient length to allow fluid to flow between the two openings when it is properly positioned.
It is usually biased to one position by a spring, and displaced to the other extreme position by a manual lever or other actuation means. If the lever is pushed to move the spool and compress the spring, the spool edges or metering notches either open or close the internal openings in the valve body, depending on the spool and body design and the initial spool position. When the lever is released, the spring forces the spool back into the initial position. This type of valve would typically be used to turn an actuator, such as a unidirectional hydraulic motor, on and off. It could also be used to connect or disconnect a function or portion of the system to supply pressure. It is usually biased to one position by a spring, and displaced to the other extreme position by a manual lever or other actuation means. If the lever is pushed to move the spool and compress the spring, the spool edges or metering notches either open or close the internal openings in the valve body, depending on the spool and body design and the initial spool position. When the lever is released, the spring forces the spool back into the initial position. This type of valve would typically be used to turn an actuator, such as a unidirectional hydraulic motor, on and off. It could also be used to connect or disconnect a function or portion of the system to supply pressure.

In the next level of spool valve complexity, four ports and internal cavities are employed in the valve body, in combination with two spool positions and at least two grooves and pairs of metering edges in the spool. This type of valve is commonly used to control rotation of a bi-directional hydraulic motor that does not require an unpowered position. Such a valve can also be used to automatically apply pressure to one side of a cylinder piston, while opening a drain path back to the reservoir on the other side. A double-acting hydraulic cylinder normally requires a three-position spool valve to provide the ability to hold it stationary, as well as to control its direction and speed. This necessitates at least four ports and multiple spool grooves and metering edges. The metering edges control pump inlet pressure as well as flow into the cylinder ports and out of the cylinder ports to the reservoir. When the spool lever is pushed by its actuation means, the pressure/drain circuit is completed, causing cylinder movement in the ‘up’ direction, and when the lever is pulled it is completed and cylinder movement occurs in the opposite direction. A captured spring mechanism is normally employed to return the spool to the centre or neutral position when the spool actuating force is removed.

The number of internal metering edges or orifices in a three-position, four-port, spool-type directional-control valve depends on the circuit design:

• In a closed-centre circuit design, the inlet pressure region of the valve spool must only block pump flow in neutral and direct it to the appropriate work port when the spool is displaced.
• A load-sensing circuit adds the requirement to drain a signal port in the neutral position and connect it to load pressure as the spool is displaced.
• An open-centre circuit allows the use of an economical fixed-displacement pump, but it means that the control valve must also incorporate additional metering edges to dump the pump flow to tank at low pressure drop in neutral, and restrict the pump’s flow path to the reservoir when the spool is displaced to build enough pressure to move the cylinder.

The basic operating principle can be extended almost indefinitely by adding ports, orifices and grooves to the valve. And, as we will shortly see, it need not be limited to a single manual actuator either. But regardless of how complex the valve becomes, the basic operation remains the same.

Poppet-type valves

In a poppet-type valve, incoming fluid is routed through an internal opening which is closed by the poppet mechanism; typically a spring- and/or hydraulically-loaded ball or conical plug. Fluid flow through the valve is controlled by the opening or closing of the poppet, which may be accomplished with a lever or other mechanical device, hydraulic or pneumatic pressure, a solenoid, or a combination of methods. In a normally closed configuration, the poppet is held against the seat by spring force and/or pressure. Moving the poppet through mechanical force, application of pressure, or venting of pressure opens the flow path from inlet to outlet. In a normally open configuration, this state and sequence are reversed and the actuation force closes the poppet. If the double-acting cylinder circuit described in the preceding example were controlled with poppet valves, two
The simplest circuits use a manually actuated spool-type valve to power the cylinder up, and depend on gravity to lower it. A slightly more sophisticated system might incorporate a load-lowering valve to limit mast speed based on load, as indicated by cylinder pressure. As mentioned above, a mast control circuit based on poppet-type valves may eliminate the need for a separate valve to control cylinder drift. It may, however, be slightly more expensive than the spool-type option.

The fork tilt function on a typical lift-truck relies on a counterbalance valve to maintain control of gravity loads by metering the fluid flow to maintain positive supply pressure to the cylinders. This function can be built into the spool-type valve, or supplied by an additional metering valve placed in the circuit between the control valve and the cylinder, or even installed on the cylinder itself. Auxiliary functions such as rotation and fork tilt can also be controlled with relatively simple circuits based on spool-type valves.

Power steering is another very common hydraulic application on lift-trucks and GSE. As steering is safety related, it needs to have priority over other vehicle functions such as mast raising. This is often accomplished with a priority valve placed in-line between the pump and the control valve. In a system having an open-centre steering unit, the priority valve will always send a fixed flow to steering, with the remaining flow available to other functions. If a load-sensing steering unit is used, the priority valve senses steering demand and proportions fluid flow between the steering circuit and other vehicle functions, ensuring that the steering flow requirement is met before flow can proceed to other functions.

The steering valve operates like a spool-type valve, except that the spool rotates rather than moving linearly. This is mounted inside a sleeve containing holes or slots that connect pressure and reservoir to the appropriate steering ports as the spool is rotated. In a load-sensing unit, as steering demand is created, a pressure-sensing line carries the signal to the priority valve which diverts enough flow to meet the demand

As noted above, steering valves may be open-centre or closed-centre types, with closed-centre load-sensing systems typically providing better control and considerably more efficiency. Steering valves also typically contain an integral metering pump to provide manually powered fluid pressure in case of engine or hydraulic pump failure.

Emerging trends
Adding electrohydraulic control capabilities to a hydraulic system greatly enhances the performance of both the system and the entire vehicle. Replacing lever-actuated directional valves with electrically operated directional valves controlled by an electrohydraulic joystick, for example, reduces operator fatigue by minimizing the amount of force required to initiate and control a machine function while simultaneously improving operational precision.

Electronic sensors and controls are now available onboard the latest valves, further integrating the electronic and hydraulic functions. Integrated sensors can be much more reliable than add-ons, and onboard electronics offer closed-loop control and diagnostic capabilities as well as CABU capability.

Electrohydraulic valves having integrated sensors and controls also give OEMs the ability to tailor system performance via software. In practical terms, that means the same valve can perform differently in different vehicles, can be adapted to the skill level or desires of the individual operator, and can change its control mode in response to actual vehicle operating conditions. This ability of one valve to perform many programmable functions can reduce costs for both OEMs and end users by minimizing spare part inventories and training requirements.

Electrohydraulic systems enable advanced capabilities such as load monitoring, closed-loop control and whole vehicle integration to improve operating efficiency. With the addition of sensors, onboard networks and computer controls, it is now possible to coordinate operation of the engine and hydraulic system in real time to optimise efficiency while meeting all applications. This capability will be increasingly important as global emission standards continue to tighten in the coming years.

It is worth remembering, however, that no matter how sophisticated these systems become, they will still be based on relatively simple devices operating on well-understood principles. That part of the equation has not changed, and will not change, no matter how sophisticated the end applications of hydraulics on lift-trucks and ground support equipment may become.