A Primer on Pulley Systems [1]

Pulley systems utilize mechanical advantage to pull weighted loads. In swiftwater rescue, hauling systems may be used to extricate a raft or canoe. Or they may be used as an integral part of a rescue system (e.g. Tefler lower). In climbing, hauling systems are used to haul gear on multi-pitched climbs and in rescue to raise or lower a liter. The major advantage of the rescue pulley systems described in this section over traditional pulley systems is that they are adjustable meaning that they can be moved along the length of the haul line.

Principles and Definitions

There are three types of basic pulley systems. They are the 2:1, the Z-rig, and block and tackle (Figure 1; see also Figure 7, Figure 8, and Figure 12). Most systems described in this section are configurations that use combinations of the 2:1 or 3:1 Z-drag. Principles and definitions included in this section include mechanical advantage, compound pulley systems, the concept of throw, self-adjusting brakes, range of system, throw, internal versus external pulling systems, and the 120° rule.

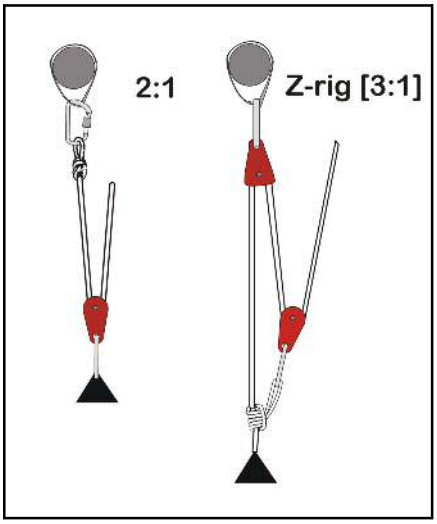

Figure 1: 2:1 and 3:1 Z-rig. Source rbk

Mechanical Advantage – The primary purpose of a hauling system is to gain mechanical advantage. There are several ways to calculate mechanical advantage. A scale can be attached to the effort and the load. Divide the weight of the load by the weight on the effort line provides the mechanical advantage. Second, measure how far the effort line moves in terms of how far the load moves. If the effort lines moves nine feet for a corresponding movement of one foot on the load, there is a nine to one mechanical advantage. Some people will count the number of lines support the load. This method may work, but with many of the complex systems it is inaccurate. For example, the double Z-rig has five supporting lines and a mechanical advantage of 9:1 (see Figure 11).

Compound Pulley Systems – These are pulley systems where one pulley system is pulling on the effort of another system. The 4:1 piggy-back is a 2:1 pulling on a 2:1 system (see Figure 9). The 5:1 is a 3:1 Z-drag and 2:1 system hooked together in parallel (see Figure 10). The double Z-rig is a 3:1 Z-rig pulling on another 3:1 Z-rig. (see Figure 11) are examples of compound systems. One technique for determining mechanical advantage is to count the supporting lines. As noted, this doesn't necessarily work for complex systems. The 9:1 double Z-rig has five supporting lines, not nine (see Figure 11).

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Self-adjusting Brake (Figure 2) – The self-adjusting brake is a prusik knot fastened to the haul line that maintains tension on the haul line as the hauling system is readjusted for a new pull. In addition, the brake provides a safety on the haul line in case for some unknown reason someone lets go of the rope.

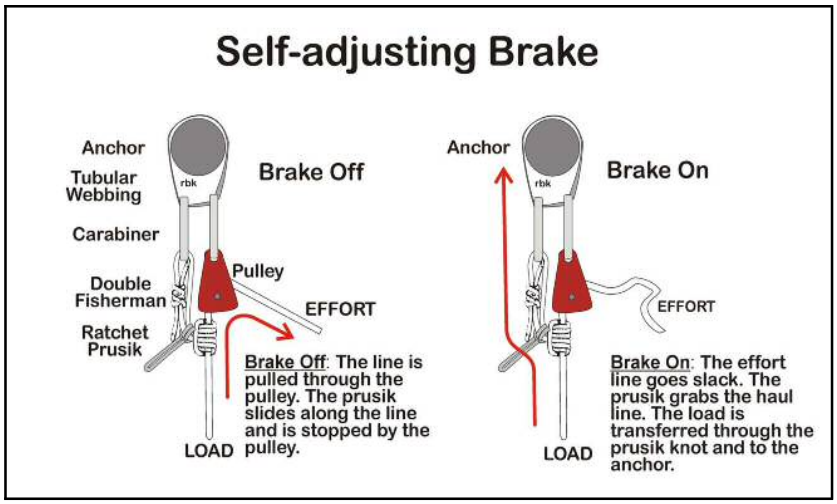

Figure 2: Self-adjusting Brake. Source: rbk

In general, the use of a prusik is preferred over mechanical devices (e.g. ascenders). In contrast to mechanical devices which tend to dig into the rope, the use of a prusik will begin to slip at around 900 lbs of pressure releasing tension on the haul line well before the braking point of the haul line. In tests where the system was pulled until it fatigued, the pressure of nylon on nylon burnt through the mantle (i.e. the braided protective sheath) and the prusik would slide down the kern (i.e. center core of kernmantle rope). This occurred at around 900 lbs of pressure. Often the prusik would slide on the haul line before the rope breaks creating a built in safety factor.

Range of System (Figure 3) – The *range of the system* is defined as the length of the hauling system. It can be as long as desired. However, there are practical limitations. As a general rule, the longer the hauling system becomes, the more cumbersome the hauling system becomes to manage. Often the range is limited by obstacles or features in the landscape.

Also, the longer the hauling system becomes, it tends to multiply the amount of rope needed to configure the system. Increase the range of a 5:1 system by one foot, and an additional five feet of rope is consumed within the hauling system to gain that one foot increase in range.

For the purposes of discussion, the range of the system is held constant in the discussion and in the drawings.

Throw (Figure 3) – *Throw* is defined as the distance the hauling system moves before it needs readjustment. Throw and range of the system are interrelated. The concept of throw

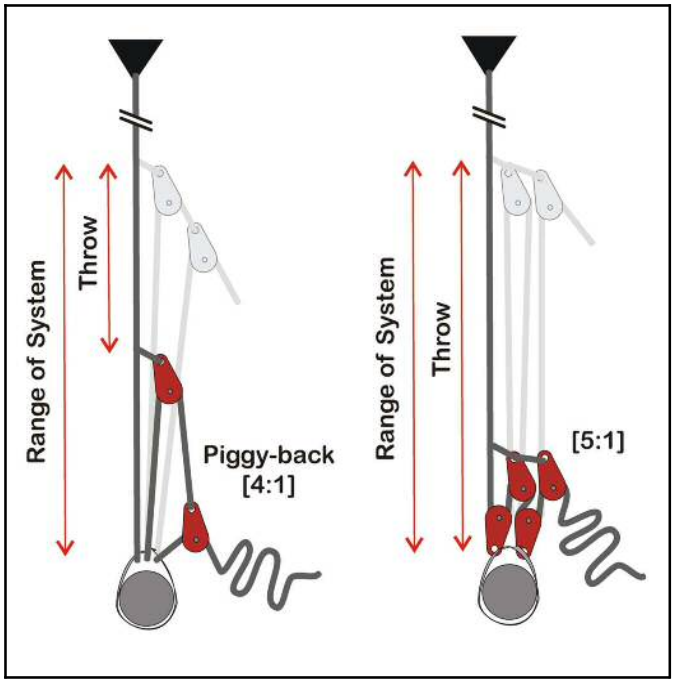

Figure 3: Range of System and Throw for Piggy-back and 5:1 Systems – The throw for the piggy-back is half that of the 5:1 system. It needs to be readjusted twice as much as the 5:1.

is demonstrated with the piggy-back [4:1] and 5:1 systems in Figure 3. The piggy-back is a 2:1 system pulling on another 2:1 system. When the system is exhausted or pulled to its limit at the anchor, the second or top pulley moves half the distance of the "range of the system." This distance is "throw." This requires the piggy-back system to be adjusted twice as often as the 3:1 Z-rig or 5:1 system which have a throw equal to the range of the system. Lack of throw makes the piggy-back more cumbersome to use.

An advantage of the 5:1 system is that it has both good mechanical advantage (5:1) and the same throw as a 2:1 system or a 3:1 Z-rig (Figure 4). This means that the 5:1 system moves the same distance as the 2:1 or 3:1 systems before it needs to be readjusted. In contrast, a 4:1 piggy-back system has half the throw as the 5:1 system. The throw for the different pulley systems discussed in this section are summarized in Figure 4.

Figure 4: Summary Table of Throw for Pulley Systems

Pulley System and Mechanical Advantage	Range of System [1] [feet]	Throw [2] [feet]	Throw as a % of Range of System [3]	Notes:
2:1	10	10	100%	Figure 7
3:1 Z-Rig	10	10	100%	Figure 8
4:1 Piggy-back	10	5	50%	Figure 9
5:1	10	10	100%	Figure 10
8:1 Double Piggy-back	10	2	20%	Not diagramed
9:1 Double Z-rig	10	3.3	33%	Figure 11
Block and Tackle [4]	10	10	100%	Figure 12

[1] **Range of the system** – The ***range of the system*** is the length of the hauling system. See discussion within the text. For purposes of this table, the range of the system is held constant at ten feet.
[2] "**Throw**" – Throw is defined as how far the hauling system moves before it needs to be readjusted. The greater the throw the less times the system needs to be readjusted. Note: The length of the pulleys and prusicks were not included in the calculation of throw.
[3] Calculation: [Throw] / [Range of System] x 100 = [% Throw is of Range of System] The length of the pulleys and prusicks were not included in the calculations.
[4] Mechanical advantage is determined by the number of pulleys used in the block and tackle. Since the pulleys are all located next to each other, throw is unaffected and is the same as the range of the system.

Internal Versus External Hauling Systems – In an *internal system*, the hauling system and hauling line are one and the same. The Z-rig is a classic example of the internal hauling system (see Figure 8). In the *external system*, the hauling system acts independently of the haul line. The Piggy-back is a classic example of an external system (see Figure 9). The piggy-back system is designed to be rigged as an external system. However, the Z-rig can be rigged as either an internal or external system.

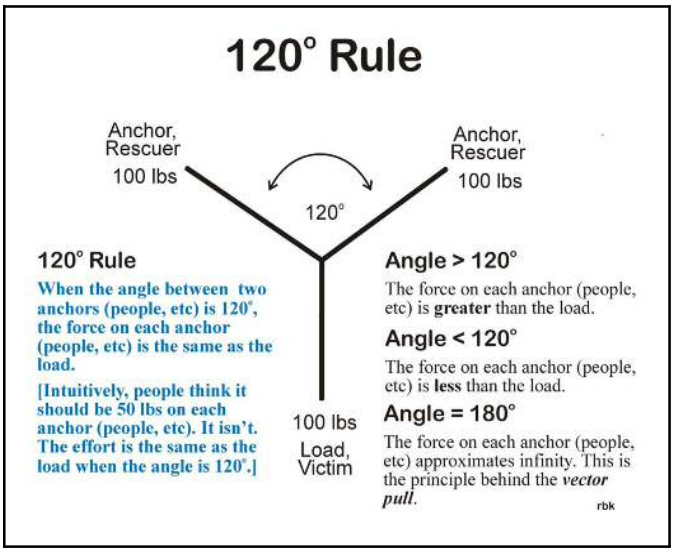

Figure 5: 120 degree Rule. Source rbk

120º Rule and Directional Pulleys (Figure 5 and Figure 6) – Derived from the climbing literature, when the angle between two anchors is roughly 120 degrees, the force on each anchor equals the weight of the load on the anchor (Figure 5). In pulley systems, when the angle between the anchor and effort is 120 degrees, the force on the anchor, effort and load are all the same (Figure 5). The result is that no mechanical advantage is obtained.

Intuitively, when using a 2:1 pulley system, the effort should be half of the load. A 20 lb effort should exert a 40 lb effort on the load or twice the effort (Figure 6). However, this is not the case when the angle is 120 degrees. It is a 1:1:1 ratio between the load, anchor and effort. Any potential mechanical advantage is lost. As the angle between the anchor and effort decreases, the mechanical advantage approaches the theoretical 2:1 ratio. A directional pulley minimizes the angle (i.e. zero angle) and maximizes the mechanical advantage (i.e. 2:1). In addition, the use of a directional pulley provides safety for the haulers since it allows them to safely stand off to the side of the hauling system in case the system fails.

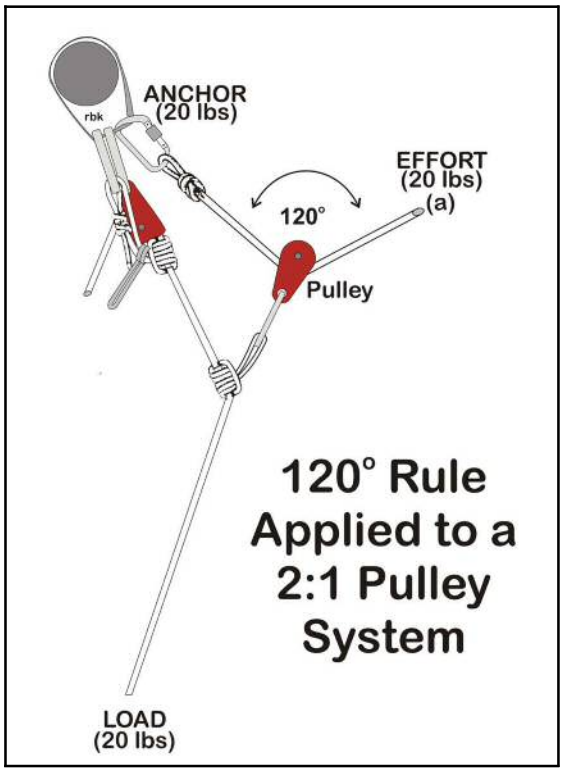

Figure 6: 120 degree Rule. Source: rbk.

Types of Systems

There are three basic pulley configurations: 2:1 Pulley System, the 3:1 Z-rig and the block and tackle. Although the block and tackle receives a minor role, it should be given more consideration as an external hauling system, particularly in search and rescue situations. For the purposes of this discussion, all of the pulley systems are a combination of the 2:1 and Z-rig systems. The block and tackle system is treated separately.

2:1 Pulley System – The 2:1 pulley system is one of the two basic systems (Figure 7). Normally, it is configured as an external hauling system. It doesn't lend itself as an internal hauling system because it can't be readjusted. Not including a directional pulley, the system can be constructed with one pulley and a prusik. The self-adjusting brake adds another prusik and pulley to the system. Throw is the same as the range of the system. As a practical matter and because of its low mechanical advantage, there is little benefit of using a 2:1 pulley system by itself. It is usually used in combination with itself in the piggy-back (4:1) and in concert with other systems such as in the 5:1 system.

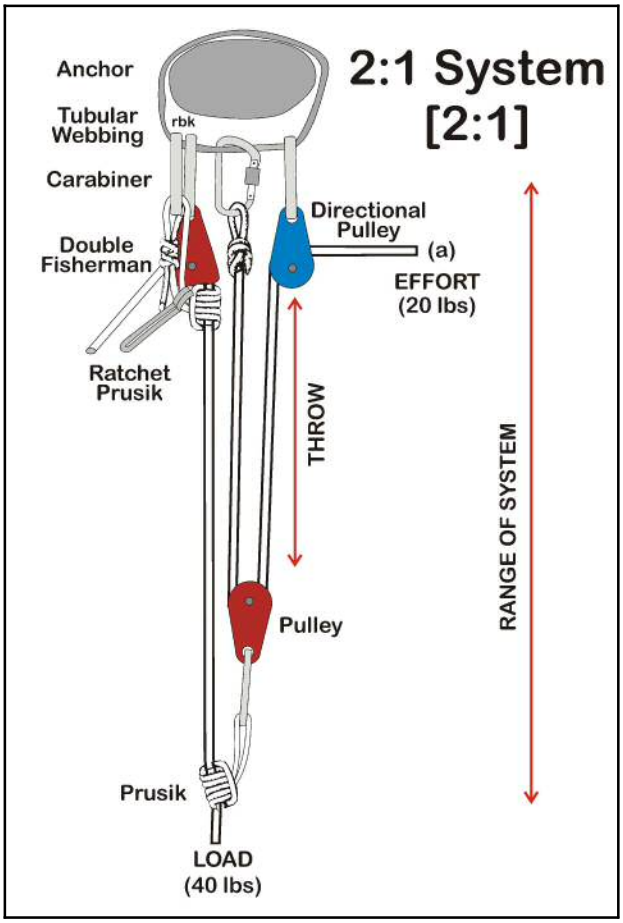

Figure 7

Z-rig (3:1) – The 3:1 Z-rig is the second basic system (Figure 8). Not including a directional pulley, the system can be constructed with two pulleys and a prusik. The self-adjusting brake adds another prusik to the system. However, another pulley is not necessary. Normally, the Z-rig is used as an internal system where the haul line is used as part of the hauling system. The Z-rig has a throw equal to the range of the system. The Z-rig can also be configured as an external hauling system. It can be used in more complex systems like the 5:1 pulley system or the double Z-rig. In some circles, the Z-rig has fallen into disfavor because with the inherent inefficiencies and friction found in any of these system, the system is closer to a 2:1 mechanical advantage in actuality. For this reason, if mechanical advantage is needed, consider the 5:1 system.

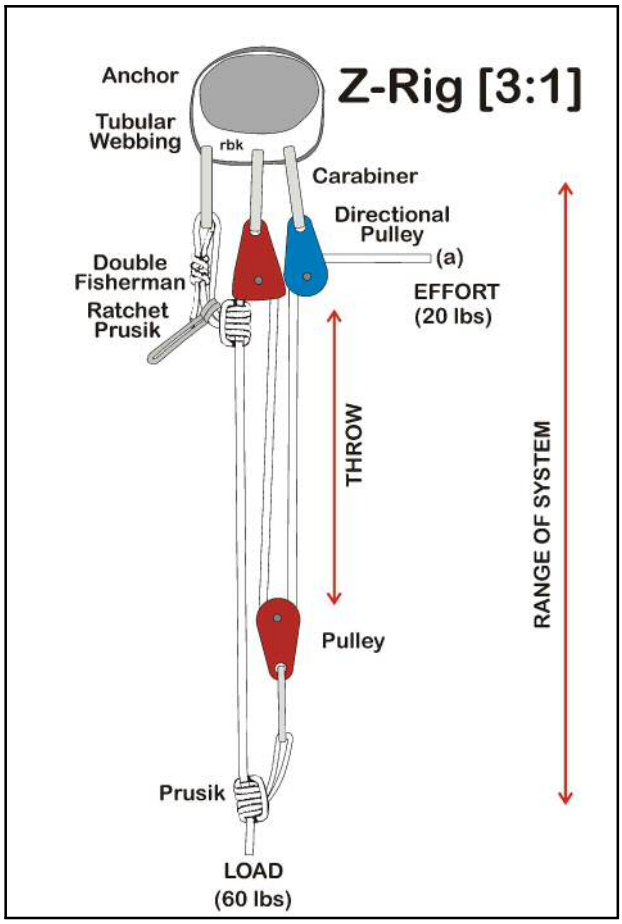

Figure 8

Piggy-back (4:1) – The 4:1 piggy-back system is literally a 2:1 pulley system pulling on another 2:1 pulley system (Figure 9). Not including a directional pulley, it requires two pulleys and a separate haul line. Obtaining a 4:1 mechanical advantage with only two pulleys can be considered an advantage of the system. The self-adjusting brake adds another prusik and pulley to the system. As a practical matter, most 4:1 systems utilize three pulleys. Although two separate lines are shown in Figure 9, a Figure 8 on a bight is often tied in the middle of a rope and the two running ends of the rope become the two haul lines. As demonstrated in Figure 3 and Figure 4, the system has poor throw or half the range of the system. Often users tend to compensate for the lack of throw by increasing the range of the system.

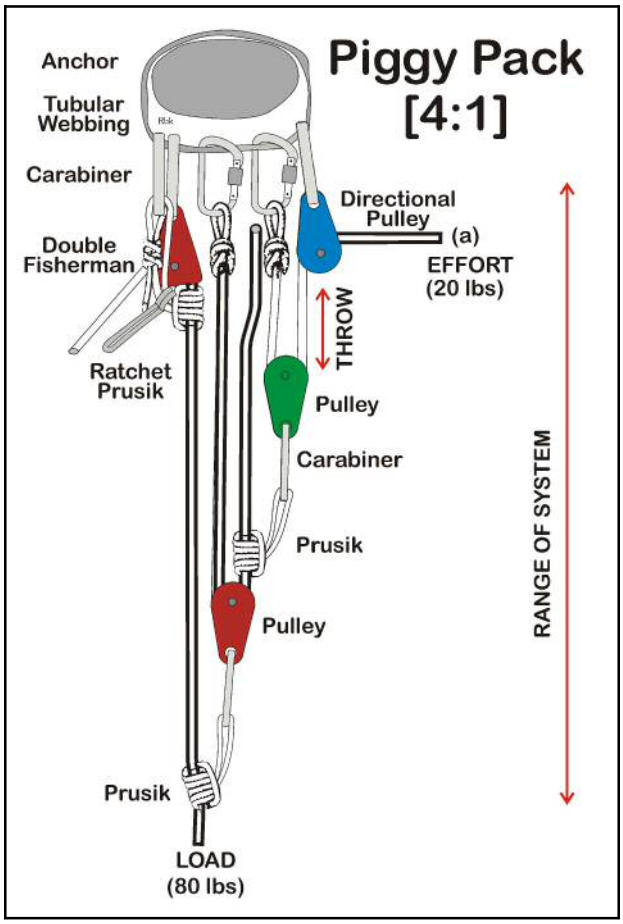

Figure 9

Consider several of the following notes regarding the use of a piggy-back system. Figure 9 shows two separate systems. A figure-eight on a bight can be tied on the effort line of the first pulley and used as the hauling system for the second pulley system.

Building on a theme of maximizing mechanical advantage using a minimum of pulleys, multiple piggy-backs begin to come into their own. In multiple piggy-back systems, mechanical advantage increases exponentially. Add another 2:1 pulley and the 4:1 piggy-back has a mechanical advantage of 8:1. Add a fourth pulley to create a double piggy-back, and a mechanical advantage of 16:1 is obtained. A disadvantage of multiple piggy-back systems is that the systems require multiple lines to construct and throw is sacrificed forcing constant readjustment of the hauling system. Comparatively, a double Z-rig requires a minimum of four pulleys for a 9:1 mechanical advantage. With an 8:1 mechanical advantage, a multiple piggy-back system requires three pulleys, one less pulley than the double Z-rig. In terms of mechanical advantage, a double piggy-back system comes into it own using four pulleys to provide a 16:1 mechanical advantage. However, the mechanical advantage is obtained at the expense of throw and there is a tendency to extend the range of the system in order to obtain a reasonable throw.

5:1 System – The 5:1 system is a 2:1 pulley system pulling on 3:1 Z-rig (Figure 10). Not including a directional pulley, it requires four pulleys. The self-adjusting brake adds another prusik to the system, but not another pulley. Since the base system is a 3:1 Z-rig, the 5:1 system is usually configured as an internal system. However, it can be configured as an external system also. A significant advantage of the 5:1 system is that it has a throw equal to the range of the system. It has the same throw as a 2:1 system or Z-rig, yet it has a mechanical advantage of 5:1. The 5:1 system has sufficient mechanical advantage to more than compensate for the practical losses of mechanical advantage resulting from the inefficiencies and friction associated with a simple 2:1 or Z-rig. This makes it an excellent alternative to these and the piggy-back systems.

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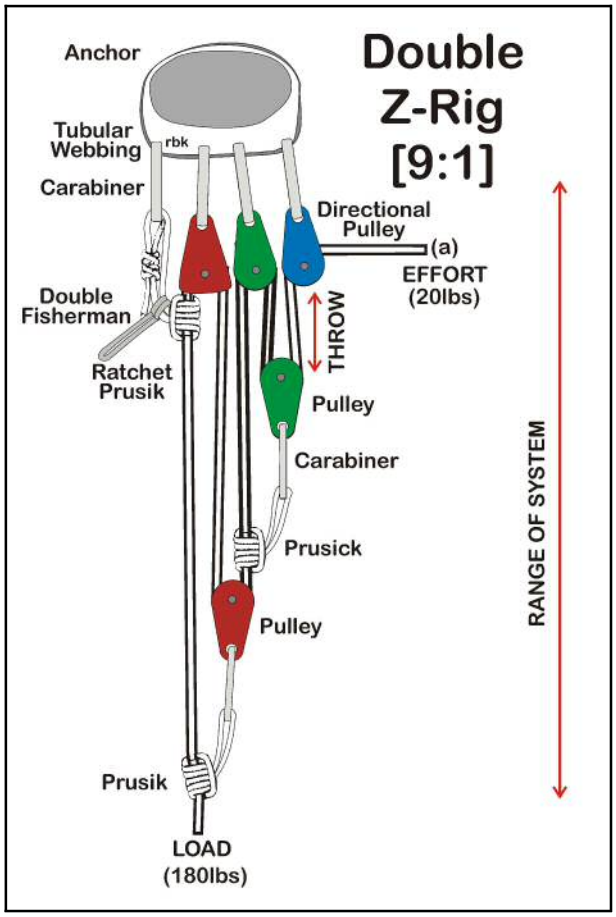

Figure 11

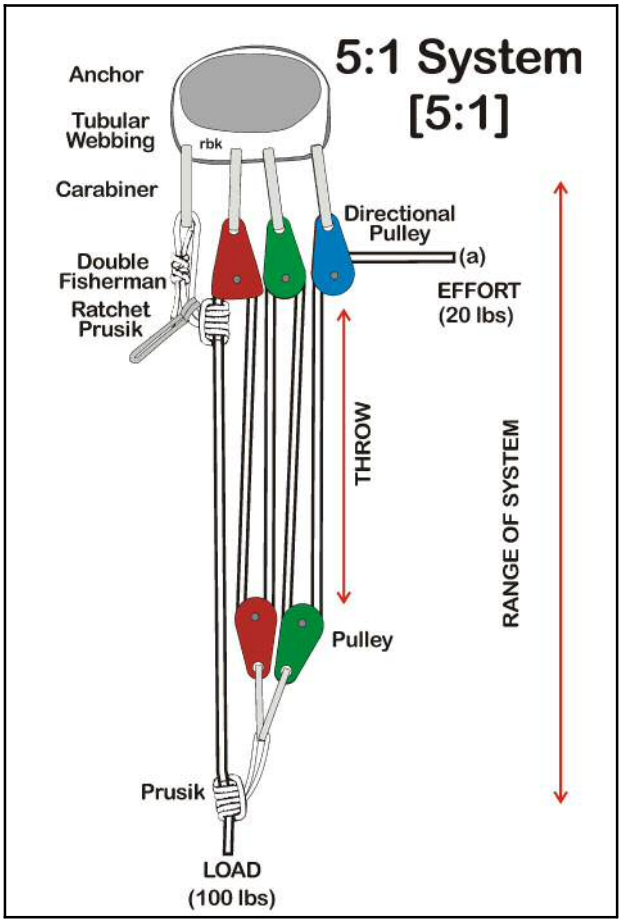

Figure 10

f needed, the 5:1 system can easily be converted into a double Z-rig, and conversely, the double Z-rig can easily be converted into a 5:1 system. To create a double Z-rig, simply unhook the 2:1 system (green pulleys) and fasten it with a prusik to the effort line of the Z-rig.

Double Z-rig (9:1) – The 9:1 double Z-rig system is a 3:1 Z-rig pulling on another 3:1 Z-rig (Figure 11). Not including a directional pulley, it requires four pulleys or the same number of pulleys as in the 5:1 system. The self-adjusting brake adds another prusik to the system. Although it is usually used as an internal system, it can be configured as an external system also. In contrast to the 5:1 system, the double Z-rig maximizes mechanical advantage at the expense of throw (see Figure 4). Comparatively, it has poor throw, equivalent to that of the piggy-back system.

The 5:1 system can easily be converted into a double Z-rig and the double Z-rig can easily be converted into a 5:1 system. To create a 5:1 system, simply unhook the green Z-rig and fasten it to the prusik on the main haul line with a carabiner.

A benefit of using a double Z-rig system is that it is an internal system. This means that the main haul line is used to configure the pulley system and no additional lines are necessary to configure the hauling system. In contrast, the piggy-back (4:1) and the multiple piggy-back systems (8:1) require additional ropes in roughly 20 to 30 foot lengths to create the haul system. This can be inconvenient.

The piggy-back is an external system. Although the double Z-rig is normally used as an internal system, it too can be configured as an external haul system if desired.

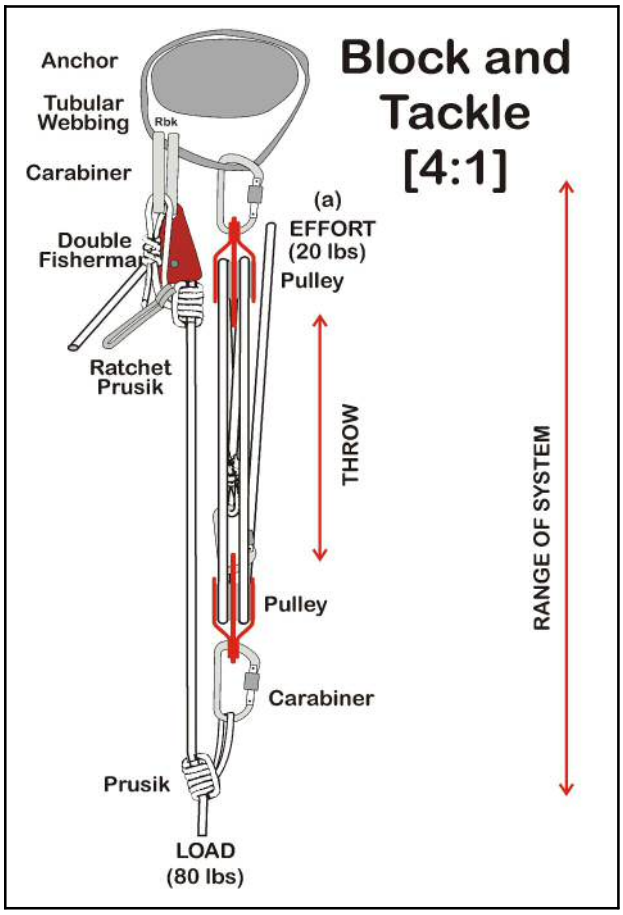

Figure 12

Block and Tackle – A block and tackle system consists of two or more pulleys pulling in opposition to each other (Figure 12). Usually, there are two or more pulleys housed within each of the two blocks or housings. When configured as an internal system, lifting is finished when the two pulleys are drawn together. The system cannot be readjusted. As an internal system, the block and tackle system is relatively impractical except for lifting heavy loads short distances.

When configured as an external system, a block and tackle system becomes a practical and efficient hauling system. In this configuration, it has a similar configuration to a piggy-back except the block and tackle is substituted for the two 2:1 pulleys. The system can have a self-adjusting brake and it can easily be repositioned along the haul line. Throw is the same as the range of the system. Also, because the pulleys are positioned next to each other, the system has better practical throw of systems where pulleys are pulling on other pulleys (e.g. double Z-rig). As pictured in Figure 11, the system provides a theoretical 4:1 mechanical advantage. Additional pulleys can be added increasing the mechanical advantage without sacrificing throw. This makes this system particularly advantageous in rescue situations. The biggest disadvantage of this system is bulk and weight making it more suitable for search and rescue teams than general recreation users. Regardless, the use of a block and tackle system as an external system has numerous advantages and in SAR situations, it can supercede most of the systems discussed on this section.

Summary

The pulley systems presented in this section are used by outdoor rescue personnel in creating rescue systems. All of the systems can be condensed into three basic systems, a 2:1, 3:1 Z-rig, and block and tackle systems. All compound systems are composed from the 2:1 and 3:1 Z-rig. The 5:1 system is literally composed of the 3:1 Z-rig and 2:1 system hooked in parallel. The purpose of the pulley systems is to increase mechanical advantage. An often overlooked factor is "throw" or how far the hauling system can operate before it needs to be readjusted. Throw makes the 5:1 system a good practical system. Figure 4 is a summary table of the different systems described in this section. It juxtaposes throw, mechanical advantage and the number of pulleys required to operate the system. The 5:1 has almost twice the mechanical advantage as the 3:1 Z-rig with an identical throw.

References

ACA Swiftwater Rescue Conference and Update, (2013). Dillsboro, North Carolina, October 25-27.

Kauffman, R., (2015). *Oar Rafting*. McHenry, Maryland: Garrett College. Unpublished packet.

Kauffman, R. (2015). *Swiftwater Rescue Packet*. McHenry, Maryland: Garrett College. Unpublished packet.

Lawrence, J., Uhl, H., Dodds, A., and Sullivan, M., (1993) *Universal Study Guide for Cave Rescue Training*. Huntsville, Alabama: National Speleological Society.

Smith, B., and Padgett, A., (1996). *On Rope - North American Vertical Rope Techniques.* Huntsville, Alabama: North American Speleological Society.