Chapter 6:
Mechanical Advantage 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 basic pulley systems. They are the 2:1, the Z-rig, and block and tackle (Figure 6.1; see also Figure 6.7, Figure 6.8, and Figure 6.12). Most systems described in this section are configurations that use combinations of the 2:1 or 3:1 Z-drag. Principles and definitions sections 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. These principles affect the effectiveness and choice of the system used.

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. Dividing 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 supporting the load. This method may work on some systems, 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 6.11).
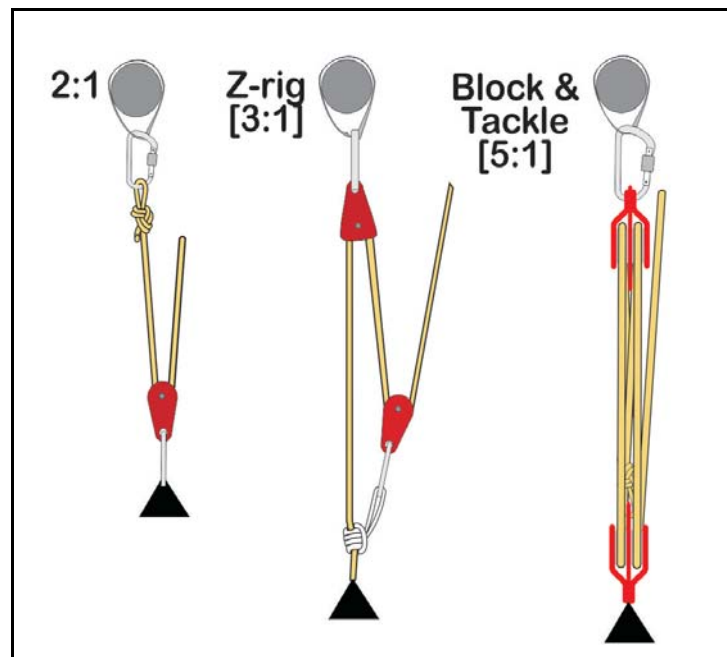

Figure 6.1: The Three Basic Hauling Systems – Source: author

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 6.9). The double Z-rig

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[1] This chapter was written and revised by Robert B. Kauffman, Ph.D. who is solely responsible for its content. This chapter is copyrighted © Robert B. Kauffman, 2020.

is a 3:1 Z-rig pulling on another 3:1 Z-rig. (see Figure 6.11) 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 compound systems. The 9:1 double Z-rig has five supporting lines, not nine (see Figure 6.11). Although the 5:1 looks like a compound system, it is really closer to the block and tackle system pictured in Figure 6.12. There are five supporting lines (See Figure 6.13).
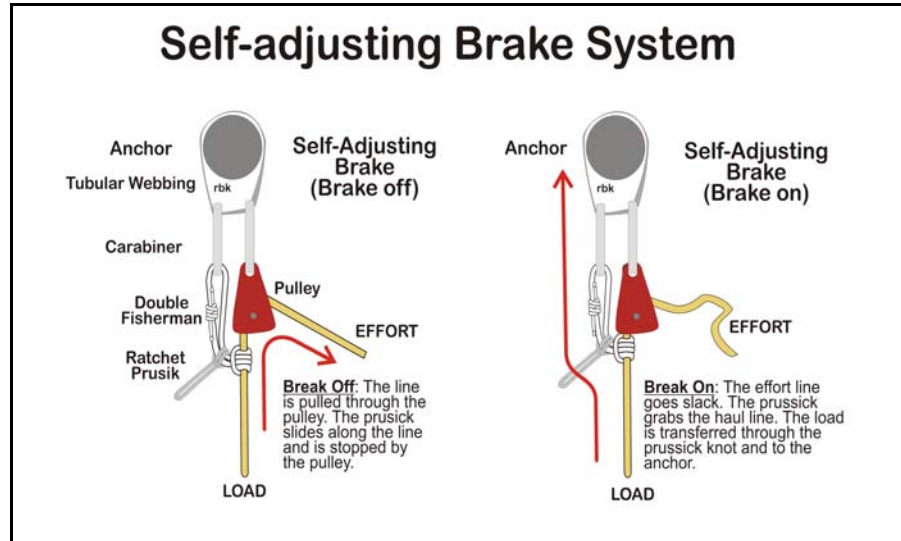

Figure 6.2: Self-adjusting Brake. Source: author

Self-adjusting Brake (Figure 6.2) – 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.

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 slid 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 broke creating a built in safety factor.

Range of System (Figure 6.3) – 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.
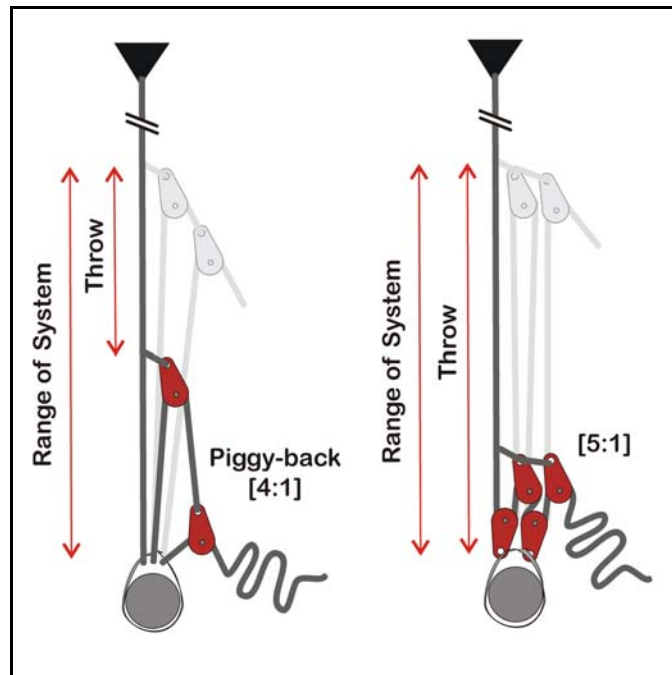

Figure 6.3: Range of System and Throw for Piggy-back and 5:1 Systems – The throw for the piggy-back is half that of the 5:1 system. It needs to be readjusted twice as much as the 5:1. Source: author

Also, the longer the hauling system becomes, it multiplies 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 needed 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 6.3) – *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 is demonstrated with the piggy-back [4:1] and 5:1 systems in Figure 6.3. 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 a more cumbersome system to use since it needs constant readjustment.

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 6.4). 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 6.4.

Figure 6.4: Summary Table of Throw for Pulley Systems [5,6]				
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 6.7
3:1 Z-Rig	10	10	100%	Figure 6.8
4:1 Piggy-back	10	5	50%	Figure 6.9
5:1	10	10	100%	Figure 6.10
8:1 Double Piggy-back	10	2	20%	Not diagramed
9:1 Double Z-rig	10	3.3	33%	Figure 6.11
Block and Tackle [4]	10	10	100%	Figure 6.12

[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 lines supporting the load. Since the pulleys are all located next to each other, throw remains relatively unaffected and is the same as the range of the system.
[5] As a practical matter, carabiners and other hardware used in setting up the systems will effectively reduce throw. The calculations do not include these realities and should be considered theoretical or ideal.
[6] Source: author

Internal Versus External Hauling Systems
– In an *internal system*, the hauling line is
used as part of the hauling system. The Z-rig
is a classic example of the internal hauling
system (see Figure 6.8). In the *external
system*, the hauling system acts independently
of the haul line. The Piggy-back is an
example of an external system (see Figure
6.9). The piggy-back system is designed to be
rigged as an external system and it can not be
rigged as an internal system. In contrast, a Z-
rig is normally rigged as an internal system,
but if desired, it can be rigged as an external
system.

120º Rule and Directional Pulleys (Figure
6.5 and Figure 6.6) – 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 (Figure 6.5). It is a
1:1:1 ratio between the two anchors and load. In pulley
systems, when the angle between the anchor and the effort
is 120 degrees, the force on the anchor, effort and load are
all the same (Figure 6.5). The result is that there is no
mechanical advantage.

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 6.6).
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 increased
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 6.5: 120 degree Rule. Source author

Figure 6.6: 120 degree Rule. Source: author

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, the
emphasis of the discussion is primarily on a combination of the 2:1 and Z-rig systems.
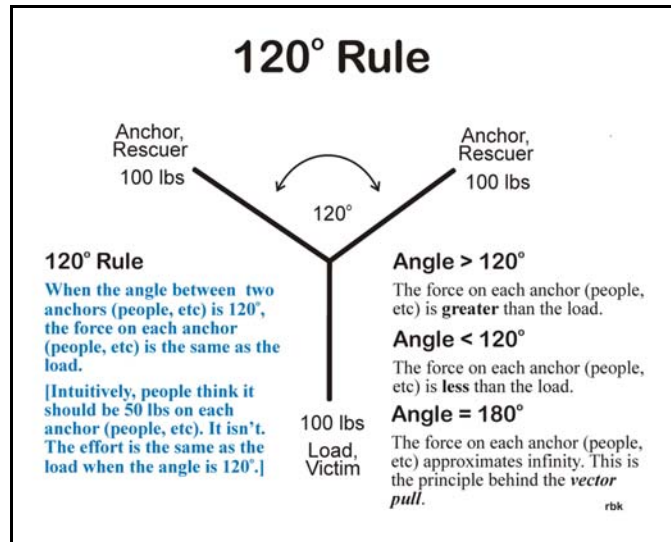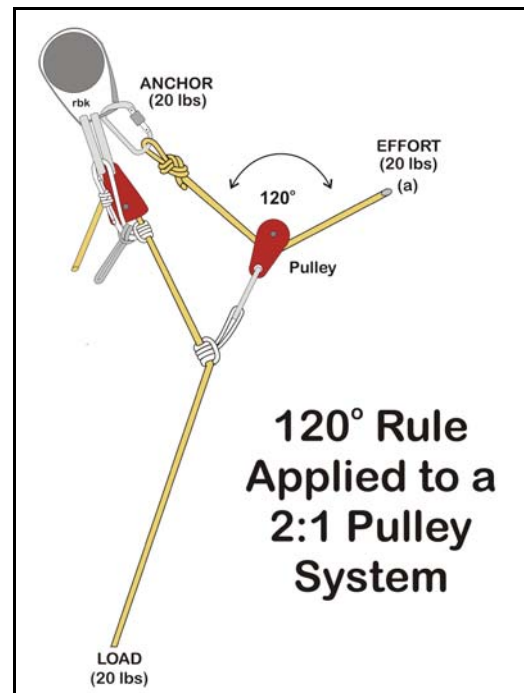
2:1 Pulley System – The 2:1 pulley system is one of the three basic systems (Figure 6.7). Normally, it is configured as an external hauling system. It doesn't lend itself as an internal hauling system because it can't be readjusted. Not including a directional pulley, the system can be constructed with 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) or in concert with other systems such as in the 5:1 system.

Z-rig (3:1) – The 3:1 Z-rig is the second basic system (Figure 6.8). Not including a directional
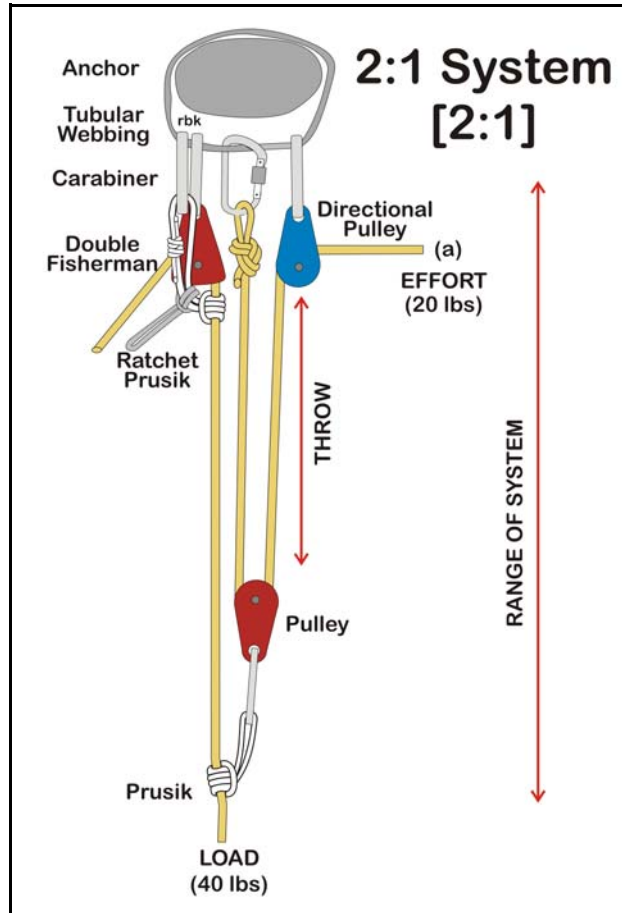

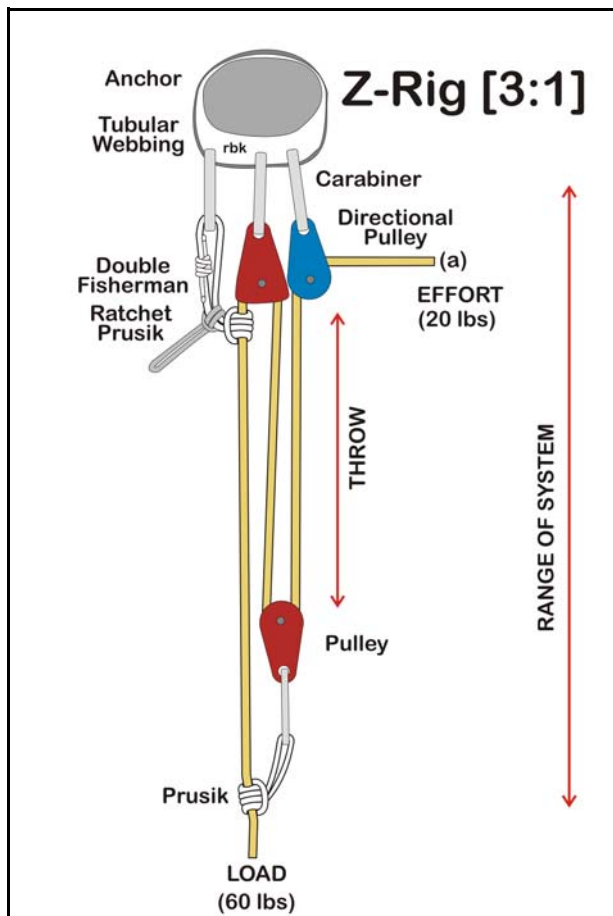**Figure 6.7: 2:1 Pulley System.** Source: author

pulley, the system can be constructed with two pulleys and a Prusik. The self-adjusting brake adds another Prusik to the system. A directional pulley adds a third pulley. 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. In practice, the system is closer to a 2:1 mechanical advantage. For this reason, if mechanical advantage is needed, consider the 5:1 system.

Figure 6.8: 3:1 Z-rig. Source: author

Piggy-back (4:1) – The 4:1 piggy-back system is a 2:1 pulley system pulling on another 2:1 pulley system (Figure 6.9). It is normally rigged as an external system. Not including the 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 however. As a practical matter, most 4:1 systems utilize three pulleys. Although two separate lines are shown in Figure 6.9, 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 6.3 and Figure 6.4, 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. However, this can become problematic also.

Consider the following notes on using a piggy-back system. Figure 6.9 shows two separate pulley systems. As previously noted, a figure-eight on a bight can be tied on the effort line and the two running ends can be used as the hauling lines for each pulley.
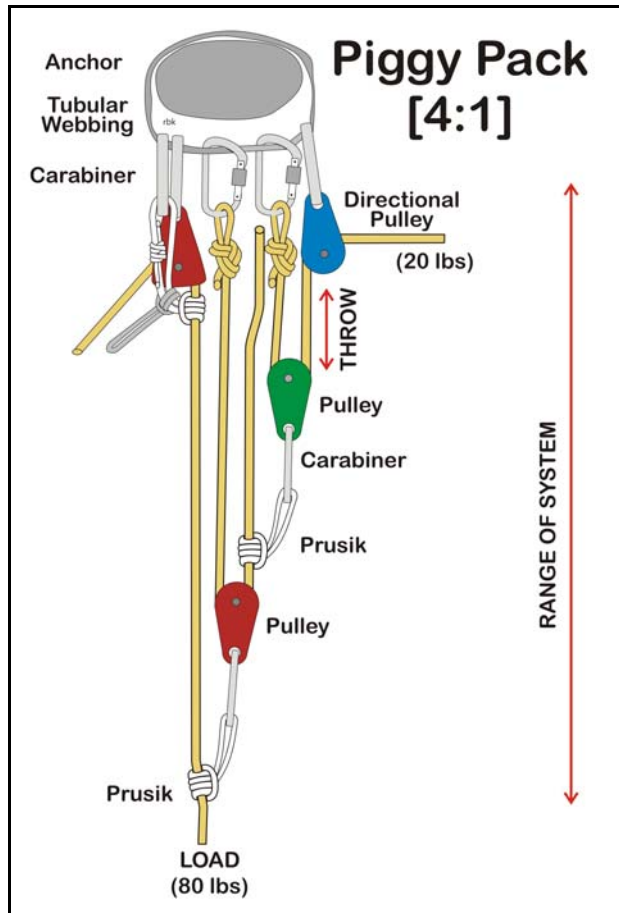

Figure 6.9: 4:1 Piggy-back System. Source: author

Building on a theme of maximizing mechanical advantage while using a minimum of pulleys, multiple piggy-backs gain mechanical advantage exponentially. However, throw is sacrificed. In multiple piggy-back systems, mechanical advantage increases exponentially. Add another 2:1 pulley onto a 4:1 piggy-back results in a mechanical advantage of 8:1. Add a fourth pulley creates a double piggy-back with a mechanical advantage of 16:1. As noted, a major disadvantage of multiple piggy-back systems is that the systems require multiple lines to construct and throw is sacrificed (see Figure 6.4). Hence, the hauling system needs constant readjustment.

5:1 System – The 5:1 system is a 2:1 pulley system pulling in parallel with a 3:1 Z-rig (Figure 6.10). It requires four pulleys and if used, a directional pulley is the fifth pulley. 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 if desired. 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. It is two extra pulley added to the haul bag.

If 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.

In the literature, this rig has occasionally been reported as a 6:1 system. This is incorrect. In actual tests using scales by this author, a 4.6:1 average mechanical advantage was obtained. The system is a 5:1 and not a 6:1 system. Close inspection of the system in Figure 6.10 reveals that it is similar to the block and tackle configuration shown in Figure 6.12 and Figure 6.13 except that the individual pulleys are housed in one block.

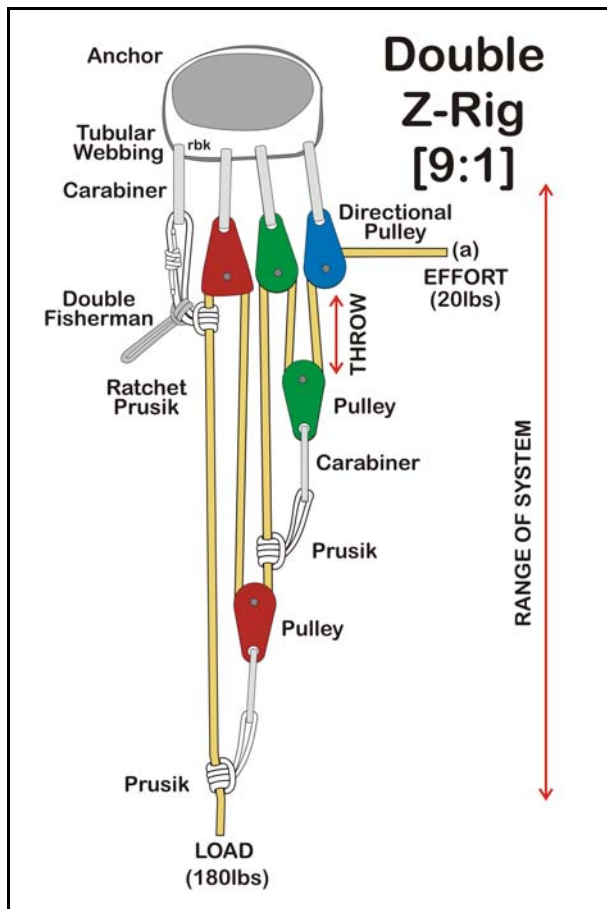**Double Z-rig (9:1)** – The 9:1 double Z-rig system is a 3:1 Z-rig pulling on another 3:1 Z-rig (Figure
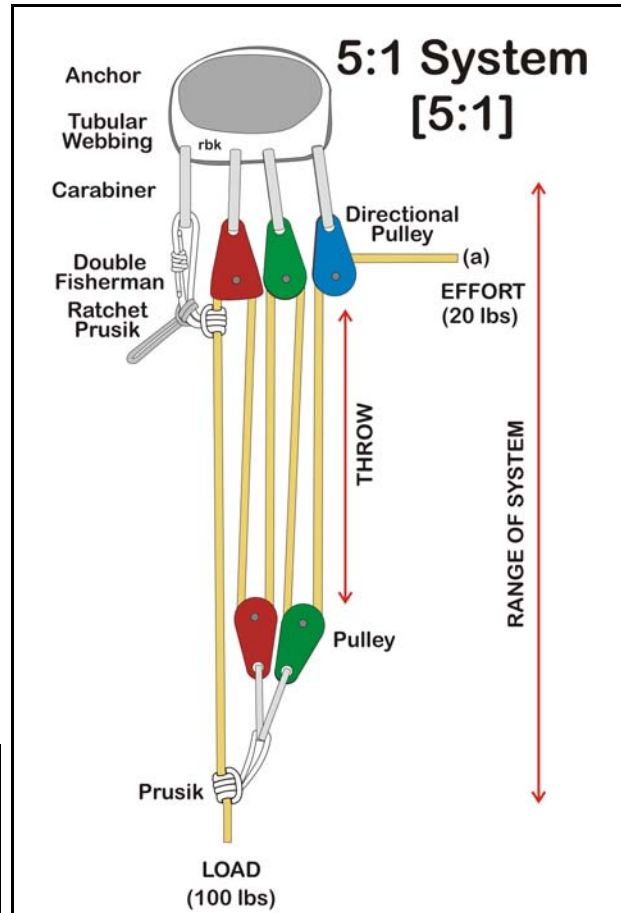

Figure 6.10: 5:1 System. Source: author

6.11). It requires four pulleys or the same number of pulleys as in the 5:1 system. A directional pulley is the fifth pulley. 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 if needed. In contrast to the 5:1 system, the double Z-rig maximizes mechanical advantage at the expense of throw (see Figure 6.4). Comparatively, it has poor throw, roughly one-third of the range of the system.

As previously noted, 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.

Figure 6.11: 9:1 Double Z-rig. Source: author

Normally, the double Z-rig system is rigged as 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. If desired, the double Z-rig can be rigged as an external system.

Block and Tackle – A block and tackle system consists of two or more pulleys pulling in opposition to each other (Figure 6.12). 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 and the system cannot be readjusted. As an internal system, the block and tackle system is relatively impractical except for lifting heavy loads short distances.

However, when configured as an external system, a block and tackle system becomes a practical and efficient hauling system. In this configuration, it is configured similar to a piggy-back or any other external system except the block and tackle is substituted for the piggy-back system. The system can be rigged with a self-adjusting brake and the system can easily be repositioned along the haul line.

Figure 6.12: Block and Tackle System. Source: author

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 compared with systems where pulleys are pulling on other pulleys (e.g. double Z-rig). As pictured in Figure 6.12, the system provides a 5:1 mechanical advantage. Figure 6.13 shows an exploded view of the pulley system. There a five lines supporting the load and since it is not a compound system (i.e. a pulley system pulling another pulley system, there is a 5:1 mechanical advantage. Also note that it has a similar configuration as the 5:1 system depicted in Figure 6.10. 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 its 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 all the advantages of the other external system discussed, and in SAR situations, it can often supercede most of the systems discussed on this section.
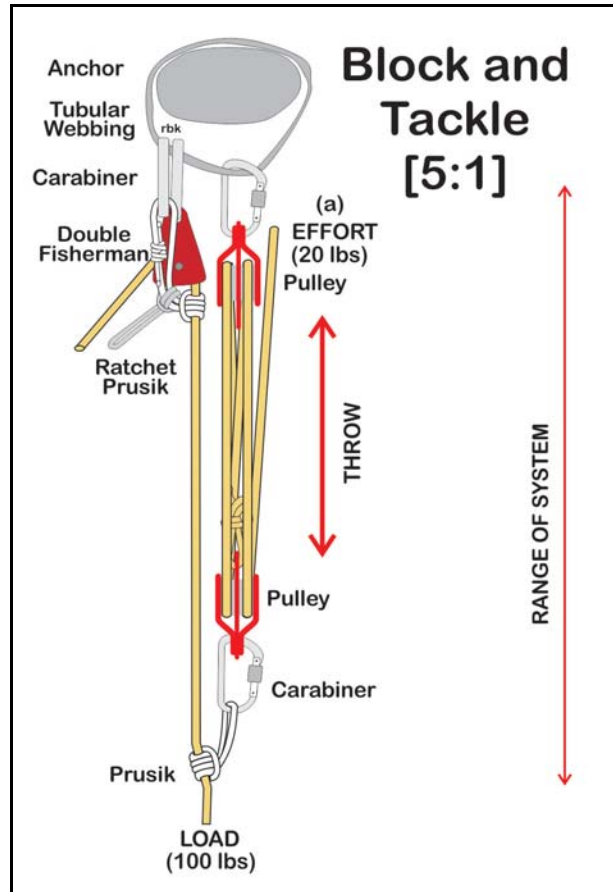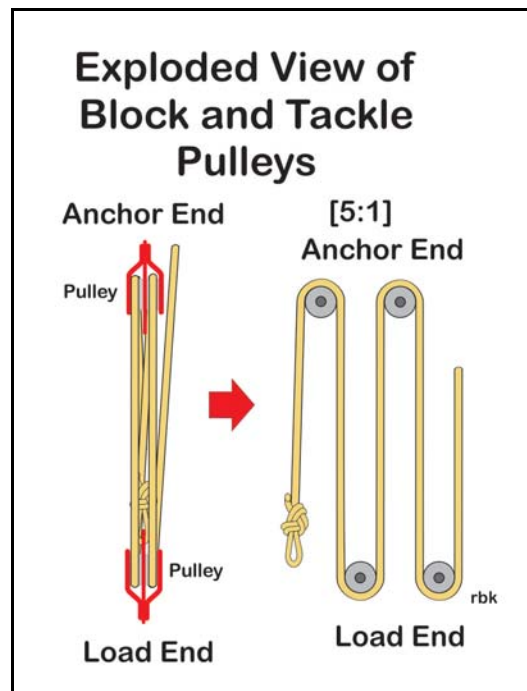

Figure 6.13: Exploded View. Source: author

Summary

This chapter is a comprehensive and thorough discussion of mechanical advantage systems. It simplifies the discussion into its basic components and moves toward a recommendation regarding which is the optimum system. Considering frictional losses, the need for mechanical advantage, range of the system, throw, and the number of pulleys required, the 5:1 system is recommended as the best all-around system.

The mechanical advantage 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 of variations of the 2:1 and 3:1 Z-rig. The 5:1 system is composed of the 3:1 Z-rig and 2:1 system hooked in parallel. In addition, haul systems are either internal (e.g. Z-rig) or external (e.g. piggy back). Some systems like the piggy back are external systems only. Others like the Z-rig are normally internal systems but can be rigged as external systems if desired. Throw or how far the hauling system can operate before it needs to be readjusted is another important consideration. The 4:1 piggy-back and 9:1 systems are hampered somewhat by reduced throw.

The need for mechanical advantage is determined, in part, by the number of people present. In the field, one of two situations is generally present. There are a lot of people present and the "arm strong" method works quite well. Nine people exerting 30 pounds each on a line will have the same force as one person exerting 30 pounds of force using a 9:1 Z-rig. If there are a couple of people available, there is a need for mechanical advantage to compensate for the lack of people. The 3:1 Z-rig sounds like a lot of mechanical advantage, but with the inefficiencies resulting from the 120 degree rule and simple friction within the system, the system is closer to delivering a 2:1 mechanical advantage in reality. As a practical matter, there is usually a need for more mechanical advantage to compensate for these inefficiencies.

In conclusion, if there is one system to know, it is the recommendation of this author that it is the 5:1 system. It has both good mechanical advantage and throw. With efficiency losses, it will still deliver at least a 4:1 mechanical advantage. In addition, if more mechanical advantage is needed, it can very easily be converted into a 9:1 Z-rig with a simple adjustment. Conversely, if less mechanical advantage is needed, the 2:1 can be unhooked and the simple Z-rig used. Practically, this most likely won't occur. In summary, if there is one system to be learn and carried in the rescue it is the 5:1 system.

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.