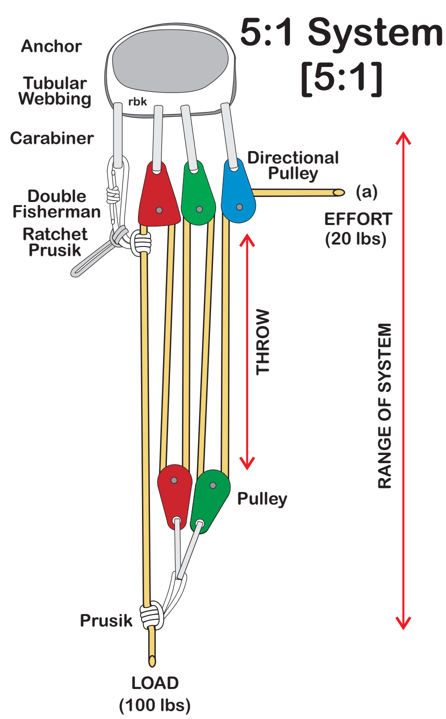
A Primer on Mechanical Advantage and Rescue Pulley Systems Used in Outdoor Settings

by

Robert B. Kauffman, Ph.D.



Forward

My interest in mechanical advantage systems originated with my involvement in swiftwater rescue. In the earlier years when swiftwater rescue was in its infancy, a lot of the techniques involved in technical climbing rescues were infused into swiftwater rescues. Some of these techniques like the Tefler Lower are still used by rescue squads, but swiftwater rescue techniques have moved to toward less complicated and less technical techniques that can be used by small groups of river runners.

In swiftwater rescue, there are times when hauling systems are needed. It could be the extrication of a raft, canoe, or kayak. Generally, one of two situations occurs. A rescue squad is present with a lot of people. Sometimes referred to as the "strong arm" method, ten to twelve people pulling on a line can exert considerable pulling strength. In the second situation, a small group of, say, three to five people needs a hauling system to augment their pulling strength. Enter mechanical advantage and the systems discussed in this pamphlet.

Along with teaching knots, I taught mechanical advantage systems in class. I remember having test questions where multiple pulley systems were presented, and the student needed to identify the mechanical advantage of the system. They looked like variations of the pulleys in Figure 13. Somewhere along the line, I saw similarities and began to make sense out of these convoluted pulley systems.

Early in the development of swiftwater rescue techniques, the Z-rig, or sometimes called the Z-drag, became popular. I would setup the 3:1 system in class in miniature using sash weight pulleys and fishing scales to measure the load and effort. I could never get a true 3:1 mechanical advantage. I eventually deduced the 120º Rule and the need for a directional pulley. Actually, I knew the benefits of a directional pulley prior to these experiments. In addition, when I needed mechanical advantage, I seemed to need more pull than a simple 3:1 system. I gravitated to the double Z-rig with its 9:1 advantage.

Key in the material's development in this publication was the introduction of the concept of "throw" and the 5:1 pulley system presented at the 2013 ACA Swiftwater Rescue Conference and Update in Dillsboro, North Carolina. I need to give recognition to the conference for their contribution. Throw is the defined as how far the system travels before it has to be readjusted. It is why the piggyback system is less efficient than the 5:1 system, which is a much better choice.

While I am on it, the 5:1 pulley system is an all-around good system with good mechanical advantage and good throw. I usually need mechanical advantage to offset not having a lot of people to pull on the effort line. If you want one takeaway from this publication, consider the 5:1 system. Add two extra pulleys and two extra carabiners to your rescue pulley bag and you can set up the 5:1 system. Add a third Prusik and you can easily convert the 5:1 to a 9:1 double Z-rig if needed.

The discussion on mechanical advantage lacked organization and simplicity in presentation. And those convoluted pulley systems still bugged me. I believe that I have accomplished these objectives in this publication. The organization and simplification of the pulley systems is potentially ground breaking and hopefully, a contribution to the field. These contributions include the concept of internal and external systems and the simplification of pulley systems into three basic systems. These are the 2:1, Z-rig, and block and tackle systems. A major conclusion is that all other systems are combinations of these three systems.

The title of this publication identifies it as a primer. It provides the basics, and that qualifies it as a primer. Again, the emphasis is on rescue in the outdoors, including swiftwater and climbing situations.

This publication originated as Chapter Six in the *Swiftwater Rescue Manual* written by this author. For the most part, the material is "standalone" and fairly generic. There have been some changes, but these were mostly editorial. The rescue pulley bag section was added. In addition, most of the pulley systems are published on their own page. This makes it convenient to copy any of the systems for use by students.

In conclusion, I believe this publication has assembled all the components necessary to describe mechanical advantage systems used in outdoor situations. The concepts of internal and external systems, compound systems, range of the system, and throw are true contribution in describing mechanical advantage systems. Some of this is new and contributes to the field.

Robert B. Kauffman, Ph.D.

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Kauffman, Robert (2022). *A Primer on Mechanical Advantage and Rescue Pulley Systems Used in Outdoor Settings.* Frostburg Maryland: Scholedale Productions. 13 pp.

A Primer on Mechanical Advantage and Rescue Pulley Systems Used in Outdoor Settings [1,2]

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 litter. 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 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 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 120º rule. These principles affect the effectiveness and choice of the system used.

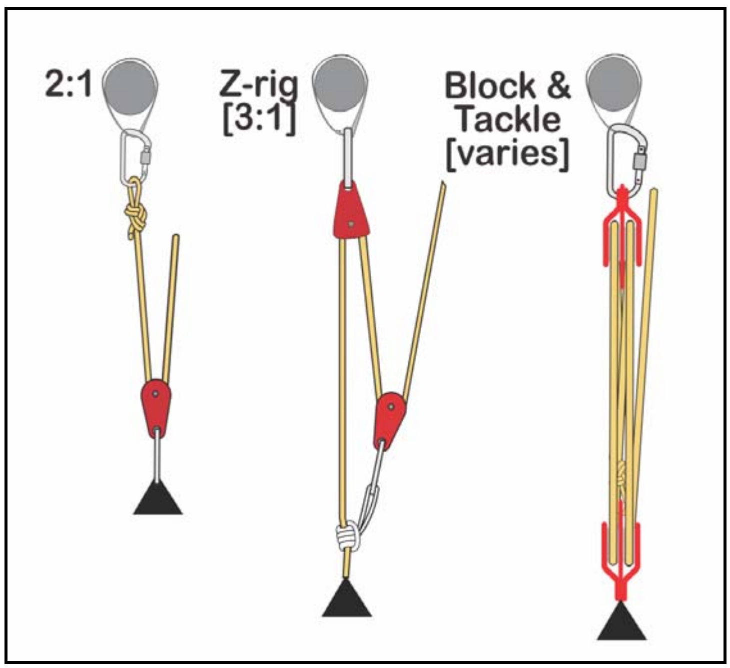

Figure 1: The Three Basic Types of Hauling Systems – Source: author.

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. Scales can measure the differences in force.

Second, measure how far the effort line moves in terms of how far the load moves. If the effort lines move

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

[2] See also: Kauffman, R. (2022). *Principles of Mechanical Advantage and Pulley Systems in Outdoor Recreation*. https://www.youtube.com/watch?v=OxmFdFkQOcE

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 simple systems, but with most compound systems, this method is inaccurate. For example, the double Z-rig has five supporting lines and a mechanical advantage of 9:1 (see Figure 11). Also, it is why the 5:1 system is a simple system and not a compound system.

Simple Pulley Systems. A simple pulley system is not a compound system where one pulley system is pulling on another. It can include multiple individual pulleys hooked in parallel (e.g. 5:1 system) or housed together in a "block" in a block and tackle system. A good indicator of a simple system is that the total number of supporting lines also equals the mechanical advantage of the system (see Figure 14). If there is doubt, use scales on the load and effort or measure the distance the load travels versus the distance traveled by the effort.

Compound Pulley Systems. A compound pulley system is 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), and the double Z-rig is a 3:1 Z-rig pulling on another 3:1 Z-rig (see Figure 11). Both are examples of compound systems. Normally, counting supporting lines to determine mechanical advantage for compound systems is inaccurate. The 9:1 double Z-rig has five supporting lines. (see Figure 11). Although the 5:1 looks like a compound system, it is really a simple system. It has five supporting lines and a 5:1 mechanical advantage.

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.

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

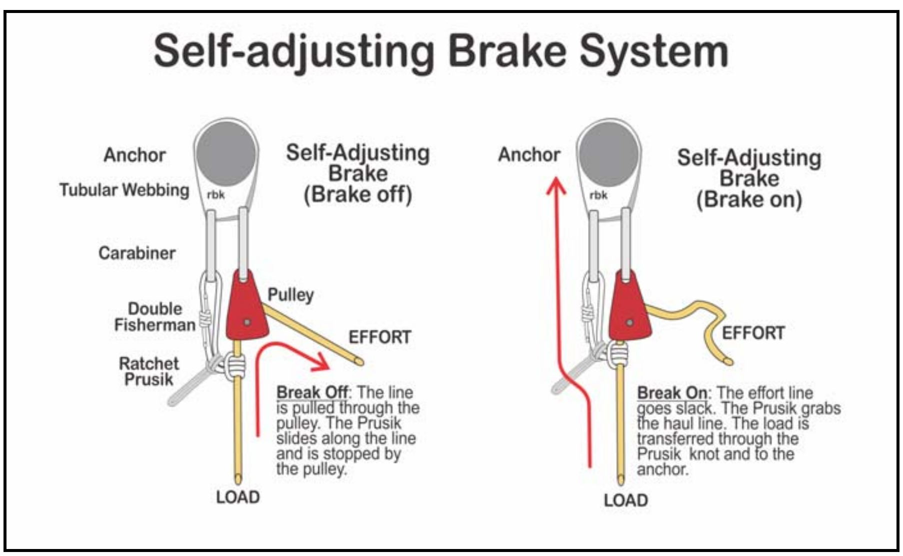

Figure 2: Self-adjusting Brake System. Source: author

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 3). The *range of the system* is defined as the length of the hauling system. There are practical limitations. The longer the hauling system becomes, the more cumbersome the hauling system becomes to manage. Obstructions can easily interfere with the haul system.

Also, the longer the hauling system becomes, the amount of rope needed to configure the system is multiplied. Think mechanical advantage in reverse. For every foot a 3:1 Z-rig is extended down the haul line, three additional feet of rope is needed to construct the Z-rig. For every foot a 9:1 double Z-rig is extended, nine feet of additional rope is needed to construct the haul system.

Throw (Figure 4). *Throw* is defined as the distance the hauling system moves before it needs readjustment. The range of the system and throw are interrelated. As a general rule, compound systems sacrifice throw for mechanical advantage.

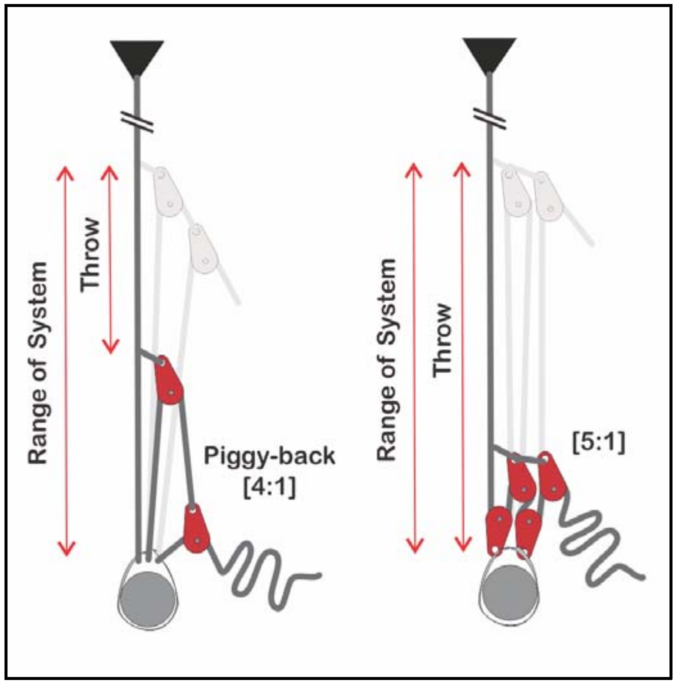

Figure 3: Range of System and Throw for Piggy-back and 5:1 Systems – The throw for the piggy-back is half that of the 5:1 system. It needs to be readjusted twice as much as the 5:1. Source: author

The piggy-back [4:1] and 5:1 systems demonstrate the concept of throw 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 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 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. Throw for the different pulley systems discussed in this section is summarized in Figure 4.

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

[1] **Range of the system**: For purposes of this table, the range of the system is held constant at ten feet.
[2] **Throw:** This figure is theoretical since it does not include the length of Prusiks and pulleys.
[3] Calculation: [Throw] / [Range of System] x 100 = [% Throw is of Range of System]
[4] If more pulleys are added to the housing, mechanical advantage will change, but throw will remain the same.
Source: author

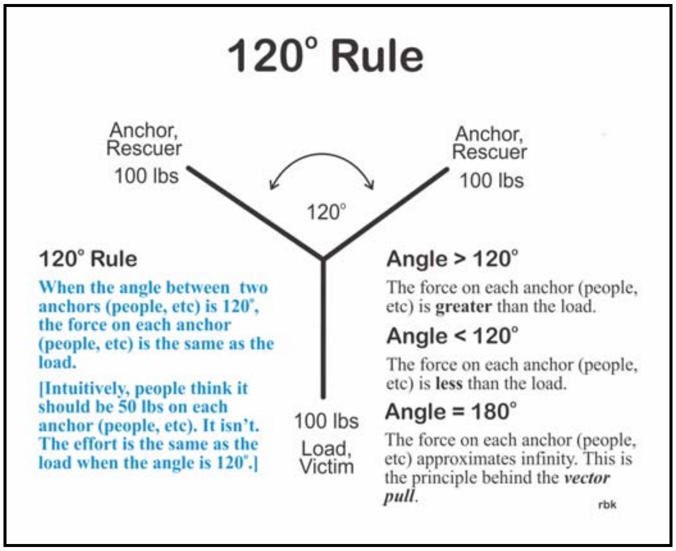

Figure 5: 120 degree Rule. Source author

<u>Internal Versus External Hauling Systems</u>. In an *internal system*, the hauling line is part of the hauling system. 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 an example of an external system (see Figure 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.

<u>120º Rule and Directional Pulleys</u> (Figure 5 and Figure 6).[3] 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 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 5). The result is that there is no mechanical advantage.

[3] See also, Kauffman, R. (2022). 120 Degree Rule. https://www.youtube.com/watch?v=SASP-c52vBk

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 increased safety for the haulers, since it allows them to stand safely off to the side of the hauling system in case the system fails.

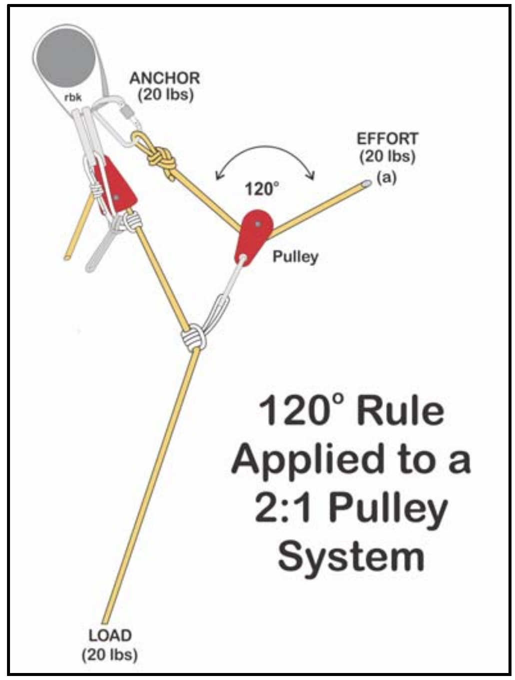

Figure 6: 120 degree Rule. Source: author

Types of Systems

There are three basic pulley systems: 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 combinations of the 2:1 and Z-rig systems.

<u>2:1 Pulley System</u>. The 2:1 pulley system is one of the three basic systems (Figure 7). Normally, it is configured as an external hauling system. It doesn't lend itself to 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 to using a 2:1 pulley system by itself. It is usually used in combination with itself in the piggy-back (4:1).

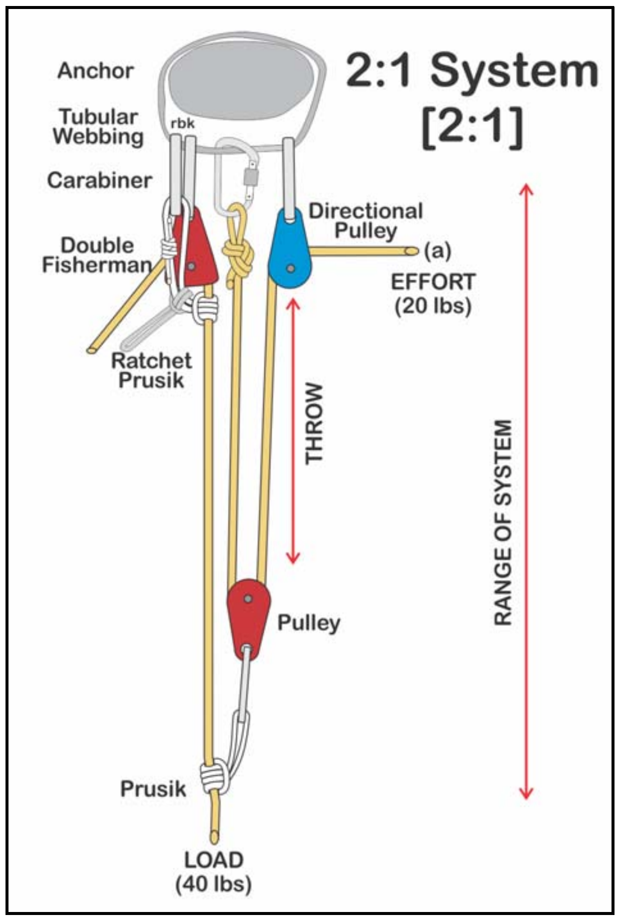

Figure 7: 2:1 Pulley System. Source: author

3:1 Z-rig. 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. 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. This is its normal configuration. The Z-rig can also be configured as an external hauling system.

The Z-rig has a throw equal to the range of the system. It can be used in more complex systems like the double Z-rig. In some circles, the Z-rig has fallen into disfavor because of the inherent inefficiencies and friction found in any of these systems. In practice, the system is closer to delivering an actual 2:1 mechanical advantage. For this reason, if mechanical advantage is needed, consider the 5:1 system.

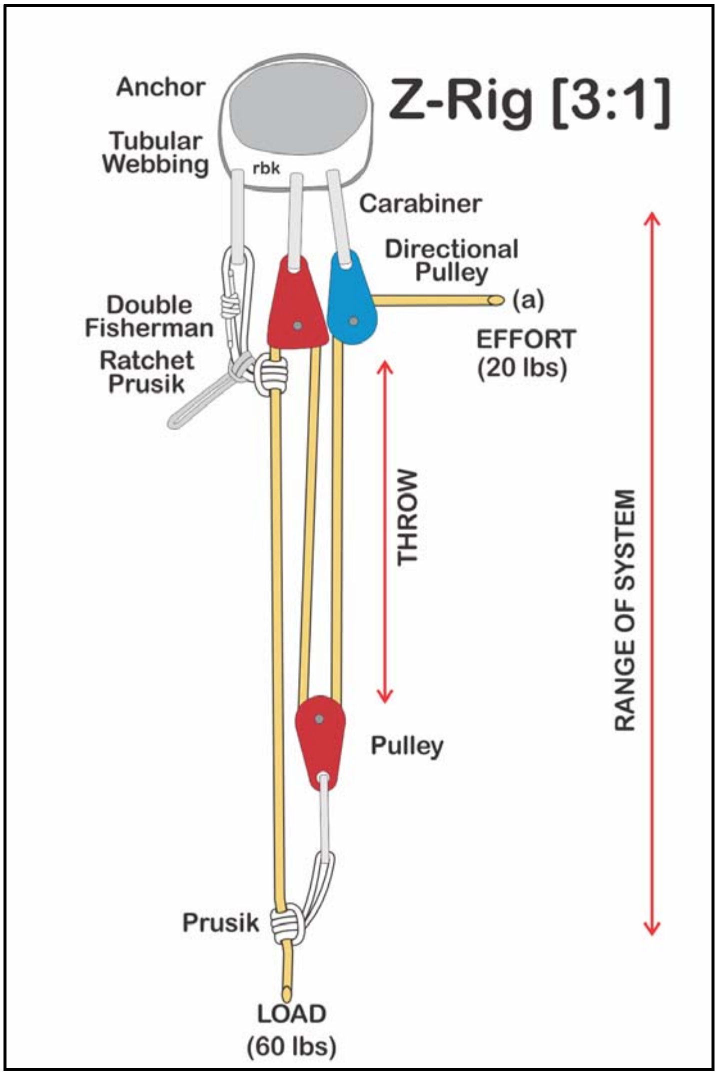

Figure 8: 3:1 Z-rig. Source: author

4:1 Piggy-back System. The 4:1 piggy-back system is a 2:1 pulley system pulling on another 2:1 pulley system (Figure 9). It is 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. 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 compensate for the lack of throw by increasing the range of the system. However, this can become problematic as well.

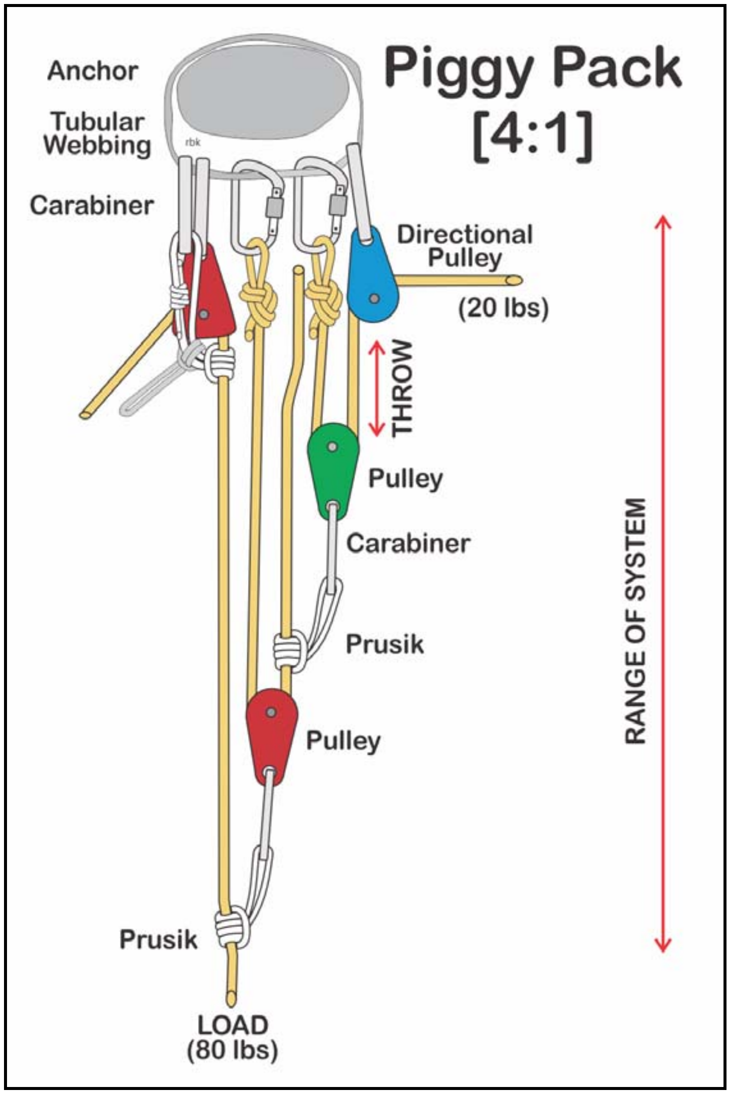

Figure 9: 4:1 Piggy-back System. Source: author

Consider the following notes on using a piggy-back system. Figure 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.

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 4). The hauling system needs constant readjustment.

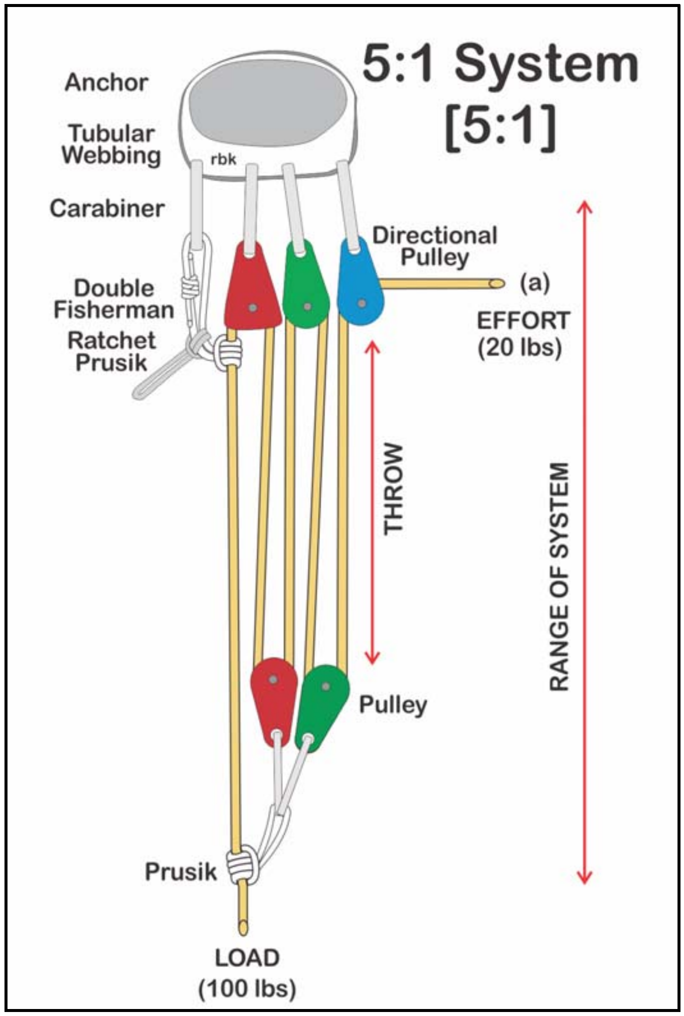

Figure 10: 5:1 System. Source: author

<u>5:1 System</u>. The 5:1 system looks like a 2:1 pulley system pulling in parallel with a 3:1 Z-rig (Figure 10). Actually, it is similar to the block and tackle except that it uses individual pulleys rather than one housing which contains multiple pulleys (see Figure 13). With the self-adjusting brake, the system has the appearance of a Z-rig with a 2:1 system attached next to it. Although making this reference is technically incorrect, it is a useful teaching technique and makes constructing the system easier. Consider using the reference "It ***looks like*** a 2:1 connected in parallel to a Z-rig."

The 5:1 system 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 behaves like 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 pulleys 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 slightly less than 5:1 average mechanical advantage was obtained. The system is a 5:1 and not a 6:1 system. Close inspection of the system in Figure 10 reveals that it is similar to the block and tackle configuration shown in Figure 12 and Figure 13, except that the individual pulleys are housed in one block.

9:1 Double Z-rig. The 9:1 double Z-rig system is a 3:1 Z-rig pulling on another 3:1 Z-rig (Figure 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 4). Comparatively, it has roughly one-third the range of other systems.

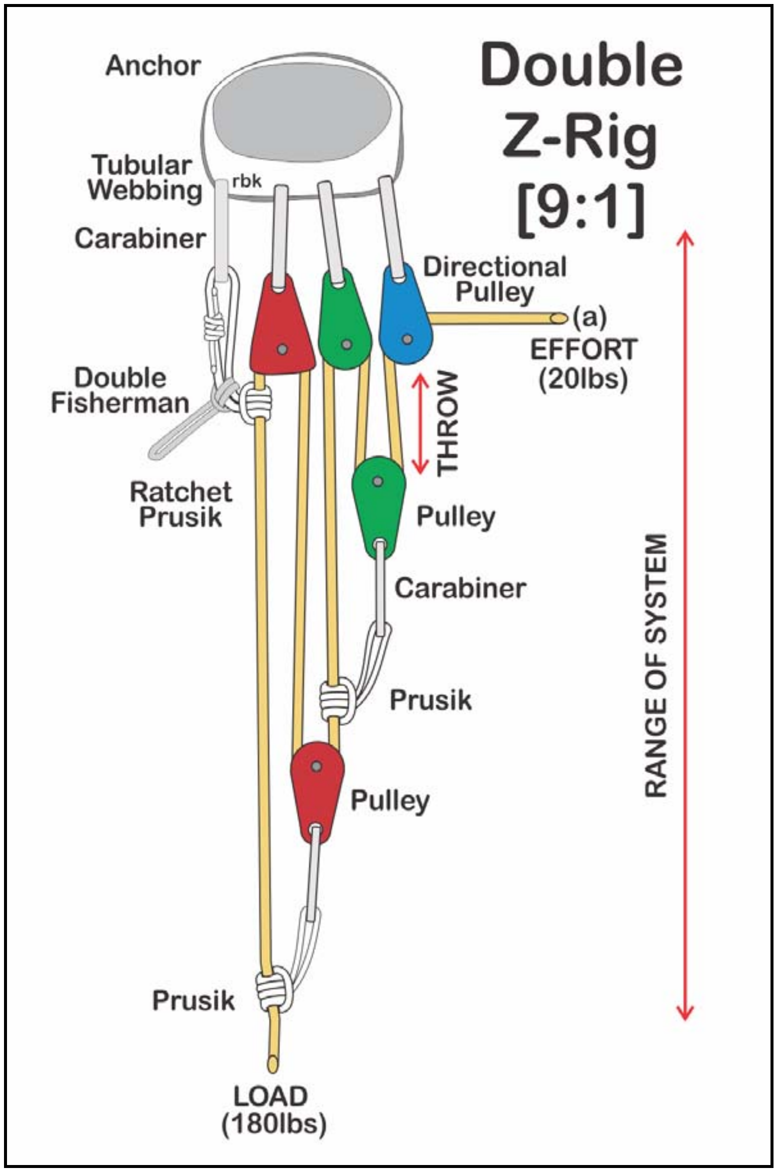

Figure 11: 9:1 Double Z-rig. Source: author

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.

Normally, the double Z-rig system is rigged as an internal system. Figure 11 shows an internal 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 in the same housing pulling in opposition to each other (Figure 12). The pulleys housed together comprise the "block." The "tackle" refers to the blocks working together as a system.

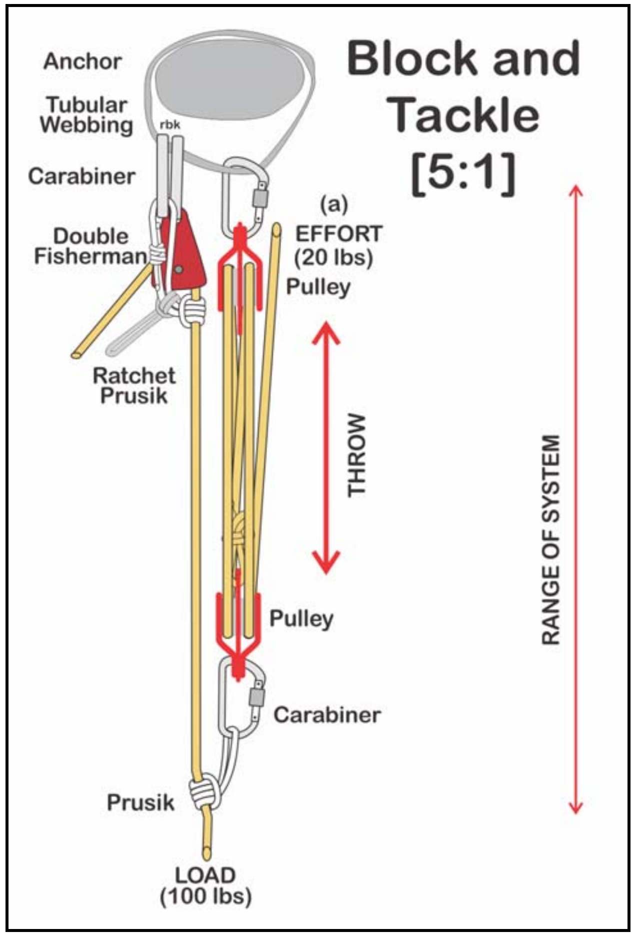

Figure 12: Block and Tackle System. Source: author

As an internal system, the block and tackle system can lift heavy loads short distances. Lifting is finished when the two pulleys are drawn together. The system cannot easily be readjusted.

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 similarly to a piggy-back or any other external system except the block and tackle is substituted for the piggy-back system. Rigged with a self-adjusting brake, the system 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 compared with systems where pulleys are pulling on other pulleys (e.g. double Z-rig). As pictured in Figure 12, the system provides a 5:1 mechanical advantage. Figure 13 shows an exploded view of the pulley system. Note that there are five lines supporting the load. 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 10.

If the pulley line is fastened to the anchor pulley rather than the load end pictured in Figure 13, the system will yield a 4:1 mechanical advantage (i.e. flip the diagram vertically). This creates one less supporting line, and the effort line is pulled toward the load end rather than the anchor end.

Additional pulleys can be added in the block, increasing the mechanical advantage without sacrificing throw.

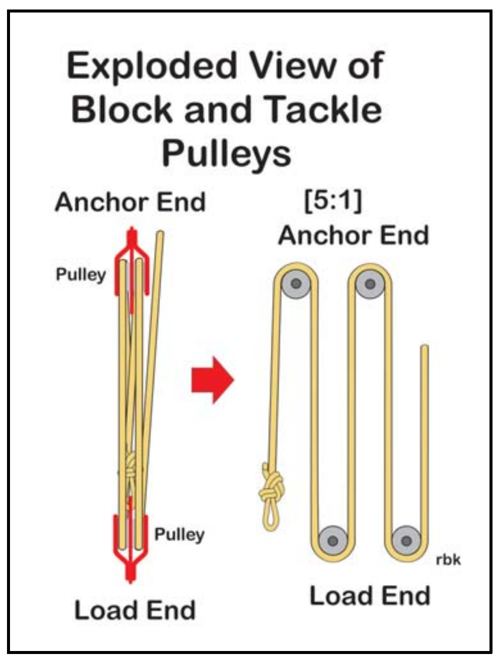

Figure 13: Exploded View. Source: author

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 supersede most of the systems discussed in this section in terms of its utility.

Rescue Pulley Bag [4]

Rescue squads engaged in high angle rescue and rafters will normally carry a rescue pulley bag, sometimes called the Z-rig bag (Figure 14). The following is a recommended suggestion regarding its contents. Often the kit will contain sufficient equipment to set up a basic Z-rig system. Contents include two pulleys and two carabiners for the pulleys. One Prusik connects the hauling system connects the hauling system to the main line. The other Prusik is used for the self-adjusting brake, and the third carabiner connects the brake Prusik to the anchor. Not shown in Figure 14, a ten to fifteen foot length of webbing is suggested to be included in the kit for an anchor.

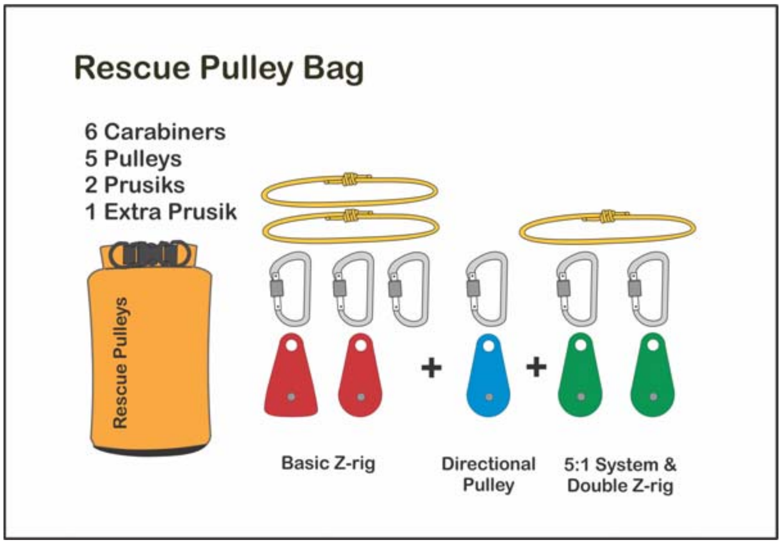

Figure 14: Rescue Pulley Bag. Consider adding two pulleys and two carabiners to be able to create a 5:1 system. Source: Author.

A directional pulley and another carabiner can be added to the kit to reduce the effects of the 120º Rule and to provide additional safety for the rescuers. Most rescuers will find that they need more mechanical advantage than the 3:1 Z-rig. Raising a litter or extracting a pinned raft may require more mechanical advantage, even with additional pullers available. Add a fourth and fifth pulley and two more carabiners and the 5:1 system with a directional pulley can be constructed. Throw in an extra Prusik and the 5:1 can be converted to a 9:1 double Z-rig can be constructed if needed.

It is recommended creating a rescue pulley bag with six carabiners, five pulleys, and three Prusiks. In addition, consider adding ten to fifteen feet of webbing for the anchor.

[4] See also: Kauffman, R. (2022). *Principles of Mechanical Advantage and Pulley Systems in Outdoor Recreation*. https://www.youtube.com/watch?v=OxmFdFkQOcE

Summary

This publication is a comprehensive 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 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. If there is one system to be learned and carried in the rescue bag, consider the 5:1 system as this system.

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