

# Understanding Mechanical Advantage in the Single Sheave Pulley Systems Used in Rescue Operations

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## Simple Machines

Consistent with other simple machines such as inclined planes and some levers, pulley systems trade *distance* for the *magnitude of applied force*. We often choose these machines when the forces available are insufficient to perform the required work through direct application of that force. For example, we generally can't simply haul on a rope and lift a litter, plus patient, plus attendant up a vertical rock face, nor can we pull a pinned, water filled canoe, off a rock in the middle of a river in strong current (the infamous "Armstrong," or "Ten Boy Scout" method). When we use these devices to help us perform work, we are saying, in effect, that we would prefer to exert a small amount of force over a long distance, rather than a much greater force over a short distance.

Consider these examples in Fig. 1:

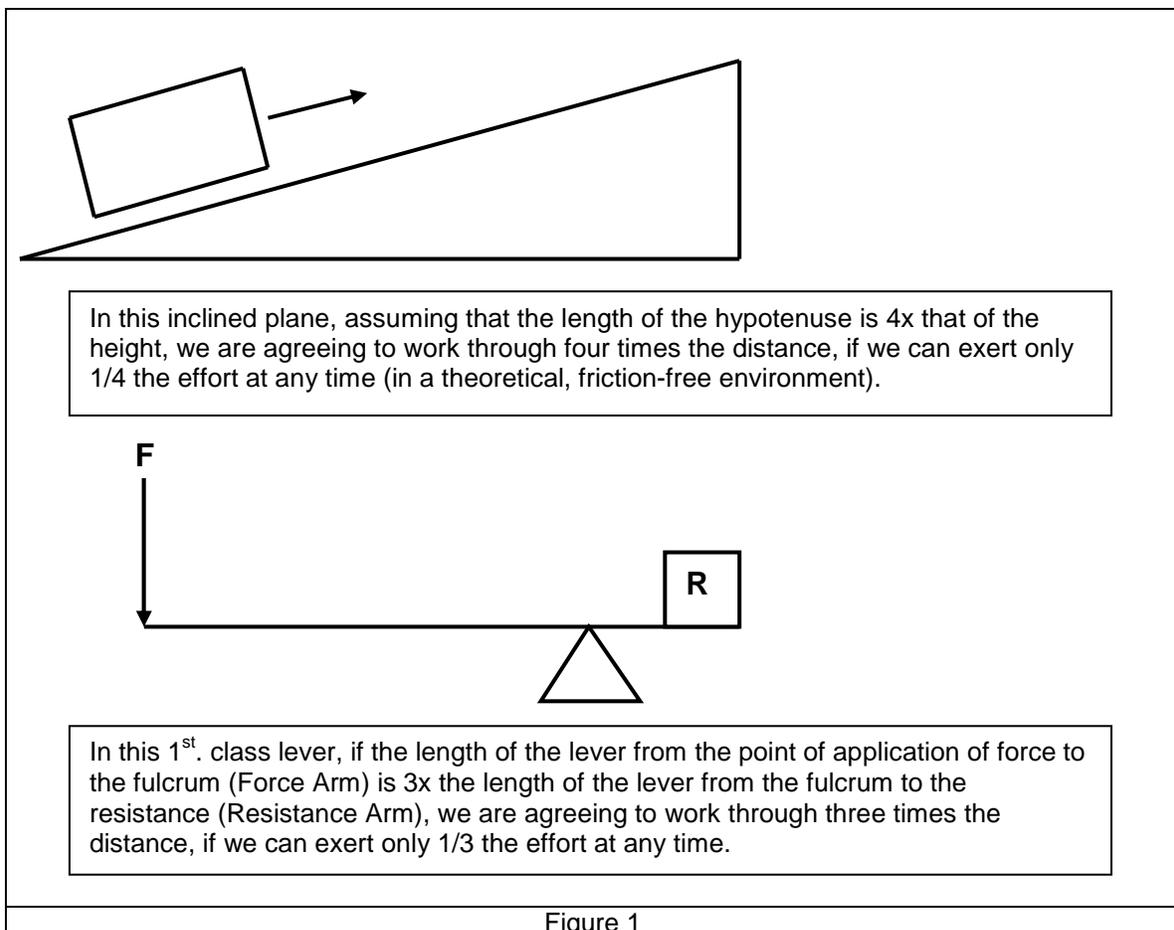


Figure 1

Single sheave (wheel) pulley systems employ the same principle; the rope and pulley configuration multiplies our force, but requires that we pull more rope through the system. A 2:1 hauling device multiplies our force x2, *but* requires us to pull 2' of rope for every 1' of movement of the resistance. By the same token, a 3:1 system multiplies the force x3, but we pull 3' of rope per 1' of travel for the resistance. It is entirely possible to create systems offering 9:1, and even 27:1 advantage by "piggybacking" one system on another. Imagine pulling through 27' of rope to move the resistance only 1'. Of course, the pay-off is that, to do so, we have to pull with a force equal to only 1/27<sup>th</sup> the load.

So far, the mechanical advantage available through use of pulley systems sounds pretty impressive—and it is—but we are forgetting one important factor: **Friction!** The MA (mechanical advantage) ratios given, are only available in a friction-free, theoretical environment. In the real world, friction reduces the actual MA—by a little, or a lot—depending on the equipment used. Even the best pulleys will reduce the actual MA of any system, and the "MA" of a rope-on-rope system, such as the "Trucker's Hitch" we might use to tie boats to a canoe trailer, can produce so much friction that the MA is essentially eliminated. The introduction of carabiners into a rope-on-rope MA system significantly increases the *safety* of that system, by eliminating the rope-on-rope friction that can cut through synthetic cordage in a matter of seconds, but it doesn't do all that much to reduce our effort. The message here is this: buy a set of rescue pulleys; and buy the best ones that you can afford, in the largest diameter you can afford to carry.

## **An Aside from Sir Isaac Newton**

The genius of Sir Isaac Newton is on full display in his laws of motion. He exhibited a wonderful ability to observe the world around him, identify patterns of behavior, and reduce the operant principles to statements that are shocking in their brevity, simplicity, and versatility.

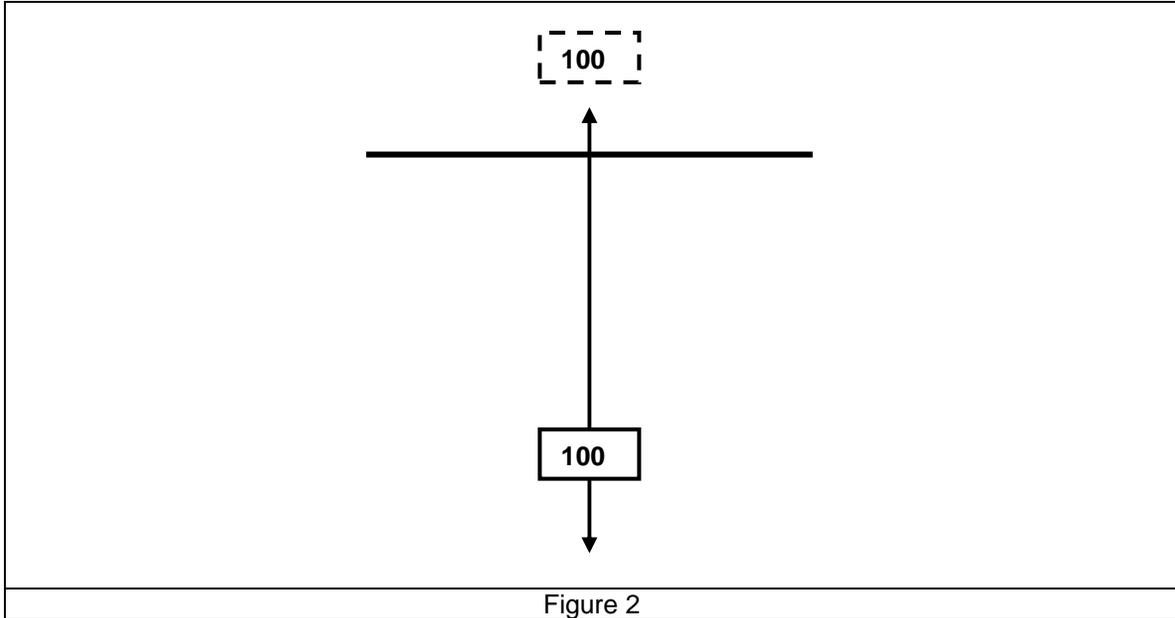
In order to fully appreciate pulley MA systems, it is essential that the reader understand Newton's "Law of Reaction." To resort to the familiar paraphrase: "For every action, there is an equal, and opposite reaction."

Consider this thought progression:

- Imagine obtaining a length of heavyweight elastic rope, the type that might be used in bungee jumping. If we tie-off one end, and pull on the other end with a 100 lb. force, it is fairly easy to accept the notion that the rope pulls back with 100 lb. force.
- Now, we'll substitute a static rescue rope for the elastic cordage, put a person on each end, and have them pull against one another with 100 lb. force: action—reaction.
- And now for the tough one, we'll ask one of the pullers from the previous example to tie-off her/his end of the rope to an immovable object. Once this is accomplished, the person at the other end of the rope resumes pulling with 100 lb. force, and the static rope *pulls* in the opposite direction with 100 lb. force: action—reaction.

If you are not accustomed to working with these concepts, this is a difficult idea to swallow; it requires a "leap of faith" of sorts. It is, none-the-less, true. If there were no reaction force at work, the person pulling on the end of the rope would fall on his/her butt. This could happen if: the rope parted, the knot came untied, or the *immovable* object—moved. If none of these three events occurs, then we must conclude that the rope is, indeed, pulling in the opposite direction with an equal force. Our static rescue rope is also capable of pulling in the opposite direction against much larger forces; but it has its limits. When these limits are exceeded, the rope breaks—and no longer produces a reaction force. Down we go.

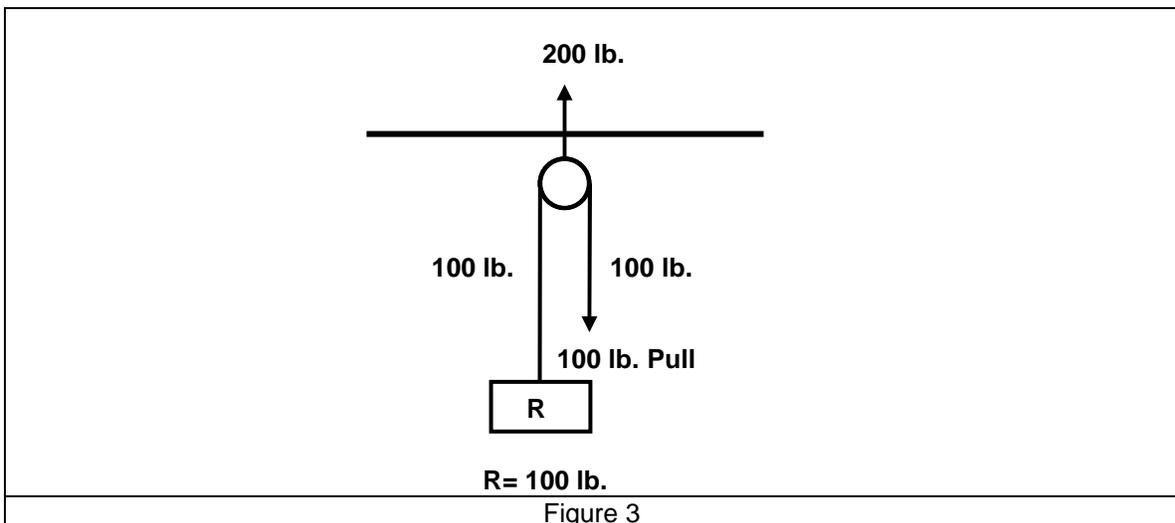
Try to accept this notion. We'll need to apply it in order to understand pulley systems. Let's begin by rotating the previous example by 90 degrees. In other words, we'll hang a 100 lb. resistance from a rope anchored to an overhead point (Fig. 2). We'll add arrows to our diagram to remind us that the resistance, on one end, and the rope and anchor on the other, are pulling in opposite directions with equal force. It will look like this:



Remember: If the resistance is 100 lb., and the rope doesn't break, and the anchor doesn't pull out, then the combination of rope and anchor must be pulling in the opposite direction, with equal force. Otherwise, the 100 lb. resistance falls. There can be no other explanation.

## Time to Add Pulleys

**Fundamental Concept 1:** In a theoretical, frictionless system (Fig. 3), a pulley equalizes the tension in both legs of the rope that passes through it. In the real world, the same *principle* applies, minus the effect of friction within the workings of the pulley in question. The quality and condition of the pulley will determine the magnitude of the friction.



**Fundamental Concept 2: Pulleys are force magnifiers!** When the two weighted legs of the rope passing through a pulley, are maintained in a parallel configuration, the forces brought to bear on the pulley's point of attachment are **doubled!** Said another way, whenever a pulley is used, it automatically transmits an increased force to its point of attachment, by a ratio of 2:1. (We'll find out why a bit later.)

This is both a good thing and a bad thing.

- Whenever we wish to move something, we can attach a pulley to it, apply the available force, and the pulley doubles that force for us, helping us to move the object. That's a good thing.
- Whenever we attach a pulley to an anchor system and apply the available force, the pulley doubles that force, increasing the strain on the system accordingly. That's a very bad thing, and we must always account for that multiplication of force when we design anchor systems for hauling rigs.

**Fundamental Concept 3:** Concept 2 would seem to suggest that pulley systems are limited to 2:1 mechanical advantage. However, by combining concepts 1 and 2, varying our points of attachment, and/or adding additional pulleys, we can create a wide variety of options.

**Time Out:** Before we go any further, let's develop Concept 2. It is crucial that we understand why a pulley doubles the forces brought to bear on its point of attachment. This set of diagrams should help.

Fig 4-A. This is an obvious review of our simple action/reaction diagram from Fig. 2. We hang 100 lb. from a rope, attached to an anchor, and the rope/anchor combination "pulls" in the opposite direction (upward) with 100 lb. of force. The anchor holds, rope remains in tact, and resistance remains suspended.

Fig 4-B. Here is the same 100 lb. resistance, with a pulley added, but with no reaction force (counterweight). The anchor holds, the rope remains in tact, and the resistance falls to the ground.

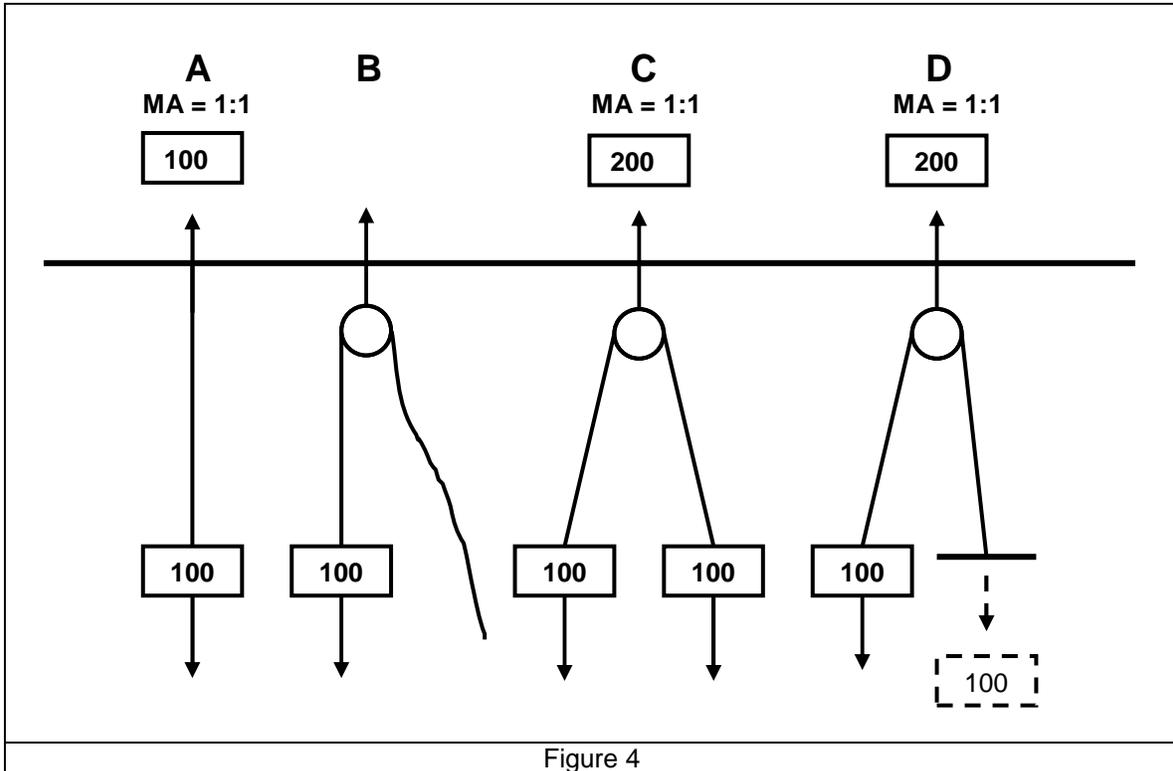


Figure 4

Fig. 4-C. B and C are the same, except that, in C, we've hung a 100 lb. counterweight from the formerly free end of the rope. Notice that the force at the anchor has doubled. The reason is obvious,  $100 + 100 = 200$ . The resistance does not move, because the forces are, obviously, in balance.

Fig. 4-D. Get out the Aspirin for this one. We suspend our 100 lb. resistance, route it through our pulley, remove the 100 lb. counterweight from the free end of the rope, and anchor it to the ground. The force applied to the pulley anchor is 200 lb.

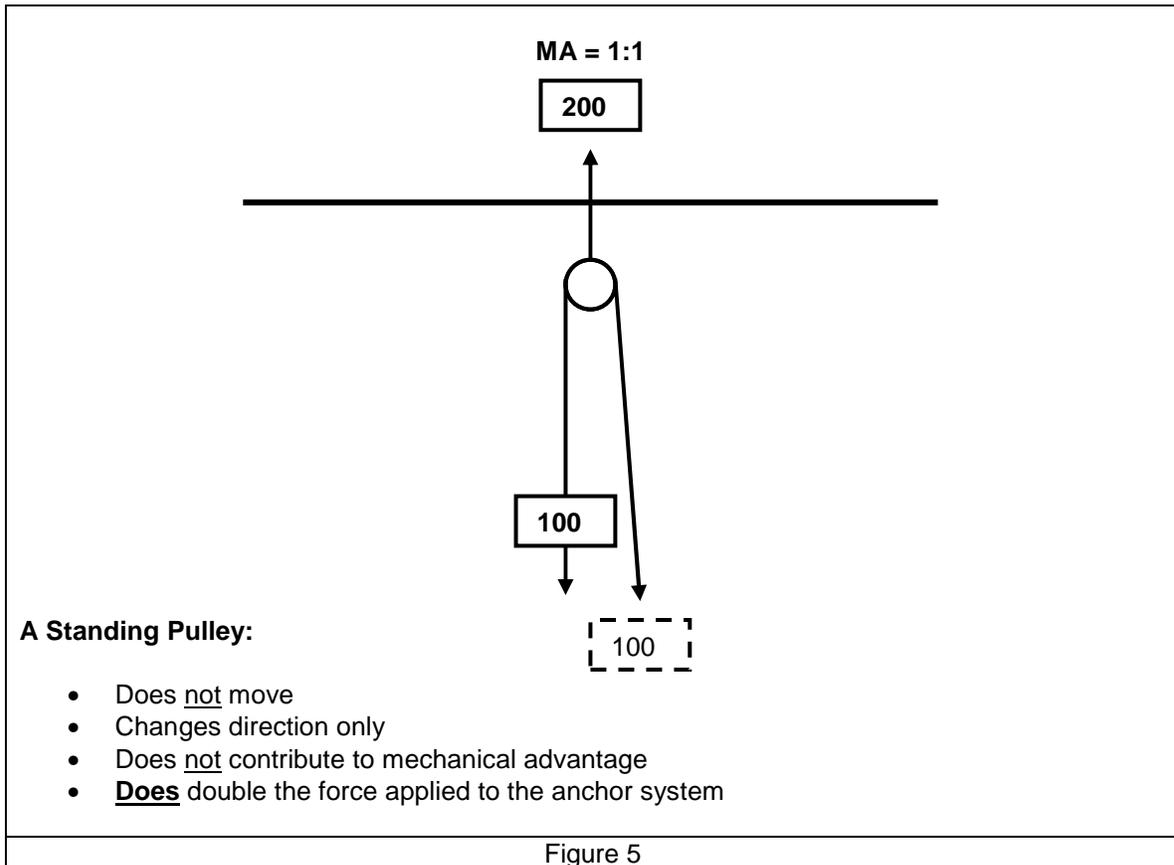
I know this seems wrong, but it's true. Go back to diagram A. The 100 lb. resistance will not remain in suspension, unless the rope/anchor combination pulls straight up with a reaction force of 100 lb. We know this is happening because the rope doesn't break, and the anchor doesn't fail. Well, it turns out that this counter-force is real, and it must be factored in whenever we calculate the stresses on our anchor points when using pulleys. As previously stated, it's a leap of faith.

Still Not convinced? Imagine yourself in diagram D. You untie the rope from the floor anchor, and the 100 lb. weight is working through a very high quality pulley, to pull upwards on the rope in

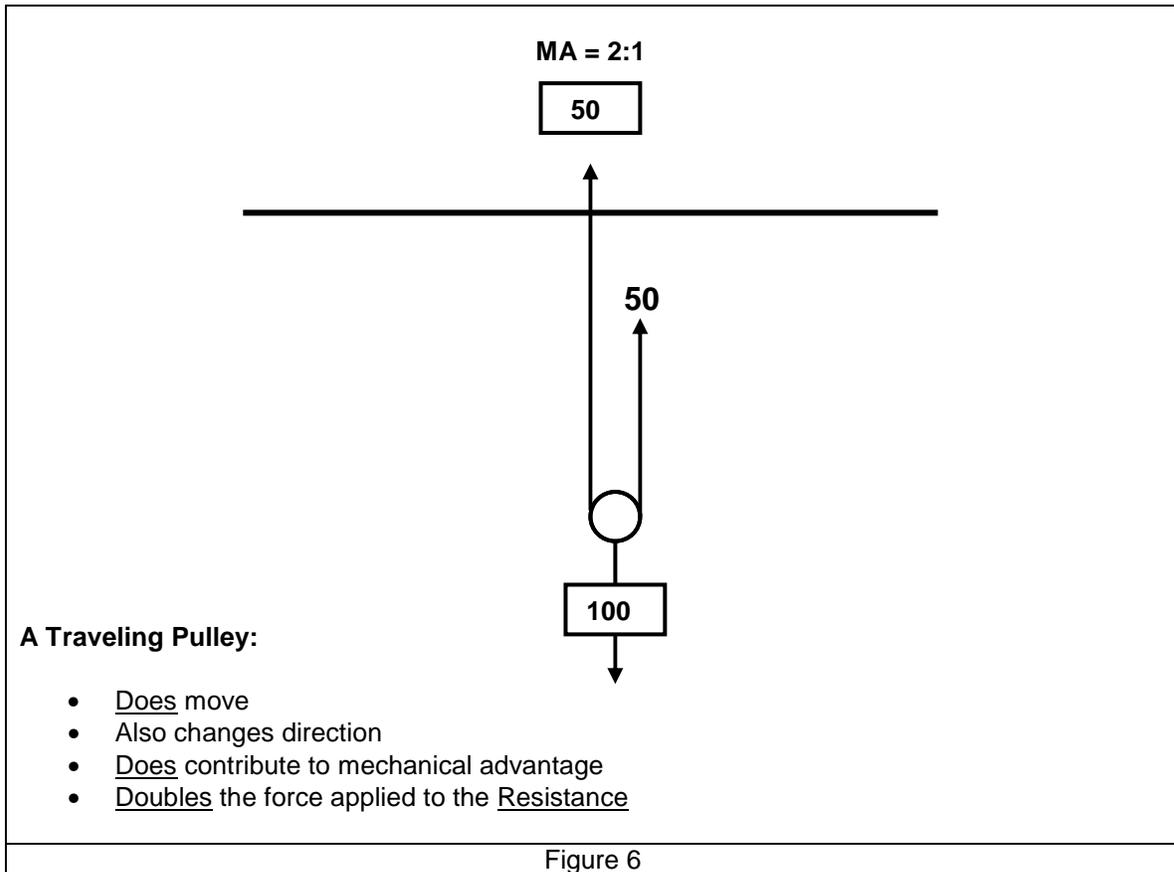
your hands, with that 100 lb. of force. You can feel the 100 lb. in your hands, your arms, and the muscles of your back. If left that way for very long, you'd become tired. It is obvious to you that you are, most certainly, pulling downward with 100 lb. force. If you were standing on a bathroom scale at the time, you would weigh 100 lb. less, because the counterweight is applying 100 lb. of upward traction. If the weight pulls down with 100 lb. of force, and you pull down with 100 lb. of force, the stress on the anchor above must be 200 lb. Growing tired of holding the 100 lb. by hand, you tie it off to the floor anchor. The stress on the overhead anchor remains 200 lb., because the floor anchor is now pulling down for you.

**Fundamental Concept 4:** Within a pulley hauling system, a pulley can function in one of two ways: as a "Standing Pulley", or as a "Traveling Pulley."

**A Standing Pulley is attached to the anchor system. It looks like this:**



**A Traveling Pulley is attached to the resistance. It looks like this:**



## **Calculating Mechanical Advantage in Pulley Systems (The easy method)**

### **Assumptions:**

- This method applies to simple systems (there are compound, and complex systems as well)
- We are using single sheave (wheel) pulleys

### **Just count rope segments:**

- We can calculate MA by simply counting the supporting lines between the pulley(s) and the resistance
- The end of the rope on which we pull is counted too, but only if it comes to us directly from a Traveling Pulley
- We'll find out why this is true later on

**Here are the basic examples:**

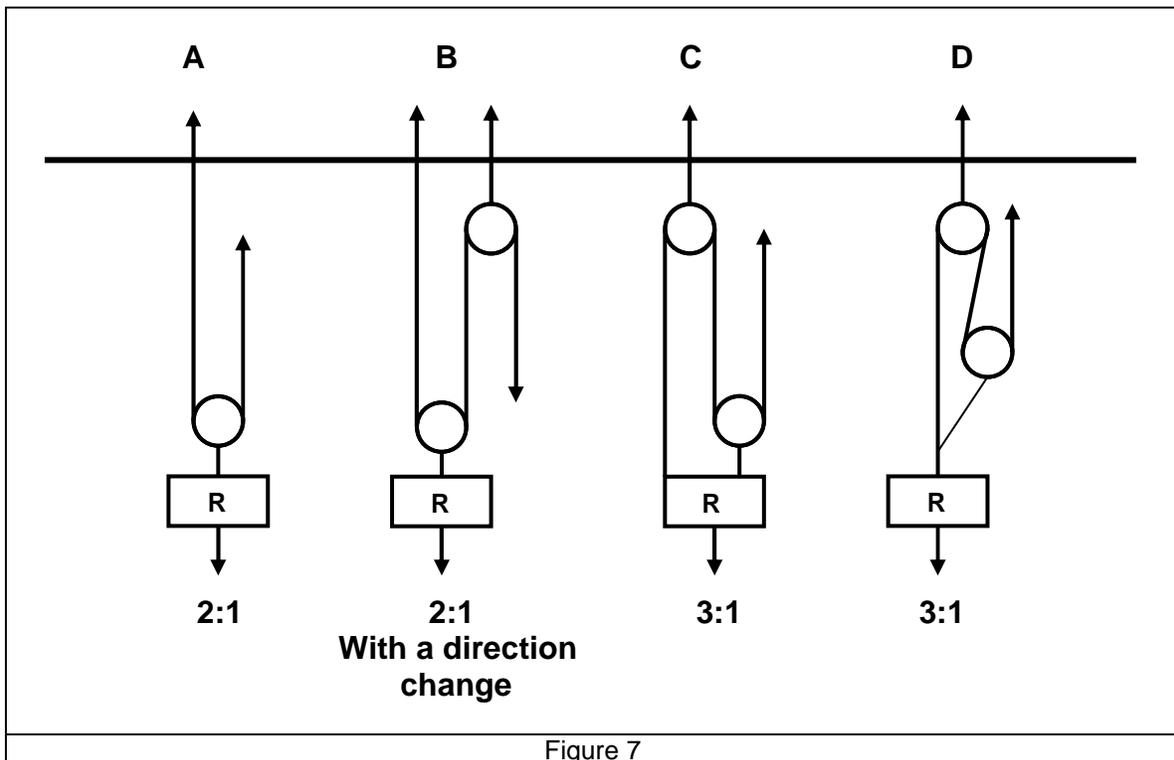


Fig. 7-A. A simple 2:1 system with one supporting line. The pulling line counts because it comes from the Traveling Pulley.

Fig. 7-B. A 2:1 system with a direction change by means of a Standing Pulley. The pulling line does not count, because it comes from the Standing Pulley.

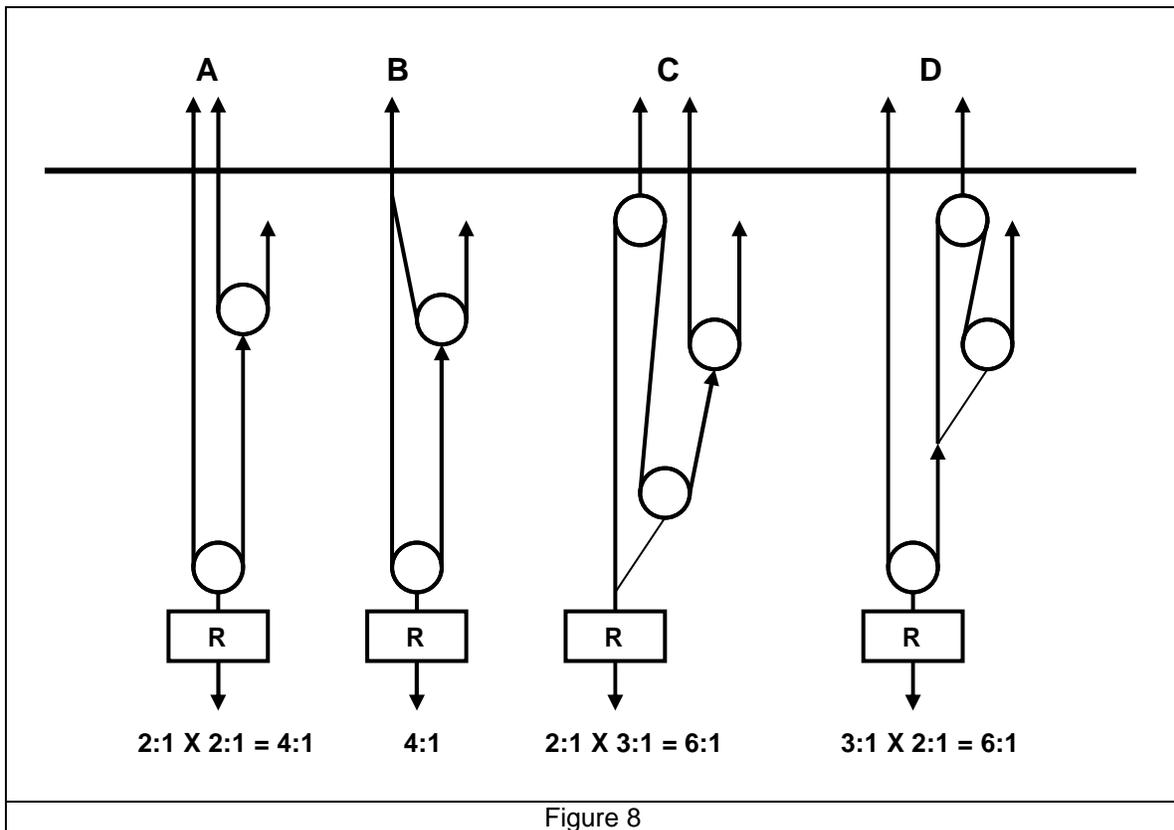
Fig. 7-C. A 3:1 system with two supporting lines. The pulling line counts because it comes from the Traveling Pulley.

Fig. 7-D. A 3:1 system as used in rescue work. The traveling pulley attaches to the main haul line with a Prusik.

**Prusik:** A Prusik is a knot that can be made to either slip or hold fast, depending on the requirements of the moment. In rescue contexts, it is generally tied using a small loop of 8 mm or 9 mm climber's accessory cord.

In the application described here, it is being used to attach the MA system to the rope itself, rather than to the resistance, which, in this application, may be several hundred feet down a vertical face. If another prusik is added to the system (not shown), it is possible to pull through a particular distance, lock off the system, re-set it, and pull again. This is called a renewable MA system.

**And—they're Stackable: Let's Learn About (Compound) Piggyback Systems in "Pig Rigs' 101"**



**To calculate the mechanical advantage of the whole system, merely figure the MA of the parts, and multiply them together.**

Fig. 8-A. A 2:1 piggybacked on a 2:1. MA:  $2 \times 2 = 4:1$ .

Fig. 8-B. Here is another 2:1 X 2:1 pig rig, this time created out of one rope, rescue-style. Make two ropes from one with a knot, in this case, most probably a figure of eight loop tied on a bight (notice the anchor, compared to Fig. 8-A). MA:  $2 \times 2 = 4:1$ .

Fig. 8-C. This is a 2:1 piggybacked on a 3:1, rigged rescue-style with a Prusik. MA:  $2 \times 3 = 6:1$ .

Fig. 8-D. Here is a rescue-style 3:1, piggybacked on a 2:1. MA:  $3 \times 2 = 6:1$

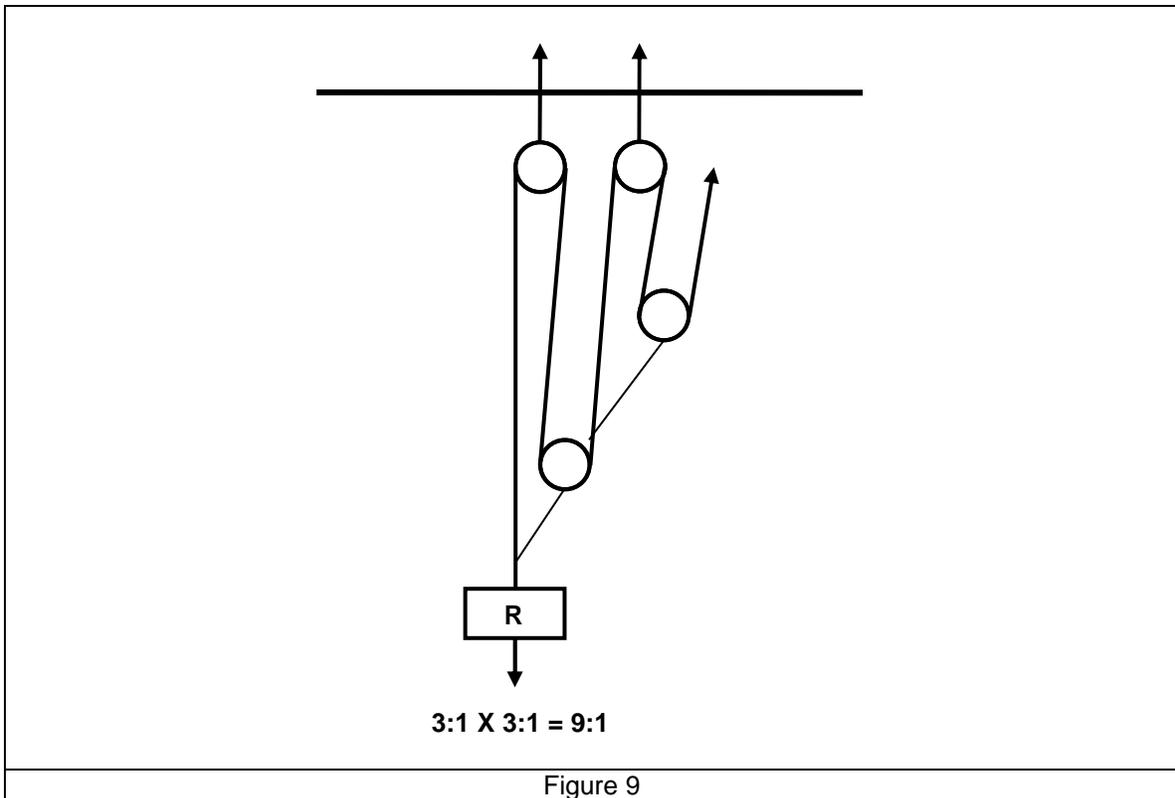


Fig. 9. This is a 3:1 X 3:1 combination, both rigged rescue-style with Prusiks. MA:  $3 \times 3 = 9:1$ . If you add one more 3:1, you create a 27:1 system.

## **Mechanical Advantage: The Inside Story**

In order to understand the source of this much-desired mechanical advantage, we need to review an earlier concept. Remember this one?

**Fundamental Concept 1:** *In a theoretical, frictionless system, a pulley equalizes the tension in both legs of the rope that passes through it. In the real world, the same principle applies, minus the effect of friction within the workings of the pulley in question. The quality and condition of the pulley will determine the magnitude of the friction.*

We use pulley systems to make things happen. We want to take the force available to us, route it through our pulley rig, and have it multiplied to produce greater force at the other end in order to perform work. The secret of this simple machine lies in the ability of the pulley to preserve the input force we apply to one leg of the rope, as it passes through the pulley, and out the other side. It does this by keeping friction to a minimum.

What this means, in practical terms, is this: if we pull on one end of the rope with our 100 lb. force, that tension will be maintained on its way through the pulley, and will persist in the same rope, on the far side of the pulley. When this happens—both parts of the rope will now apply their respective 100 lb. of force to the pulley, for a total of 200 lb. The pulley receives 200 lb. of force. Remember, the pulley is a force multiplier. Now we know how this is accomplished. It's a difficult idea to swallow, but it's true.

If we add more pulleys, and more attachment points, the input force is—theoretically—passed throughout the system—undiminished! This explains why we can calculate MA by merely counting supporting legs of rope, plus the free-end, *if* it comes to us from a Traveling Pulley. Let's apply this new idea to our system diagrams. To simplify things, we'll use the notation "T" for "tension," plus a number, to help us keep track of how much. Our standard, starting input tension will be T 1. If this is confusing, feel free to stick with our 100 lb. as a standard input force. Call it "T 100" (I'm just tired of typing zeros).

**Consider these examples:**

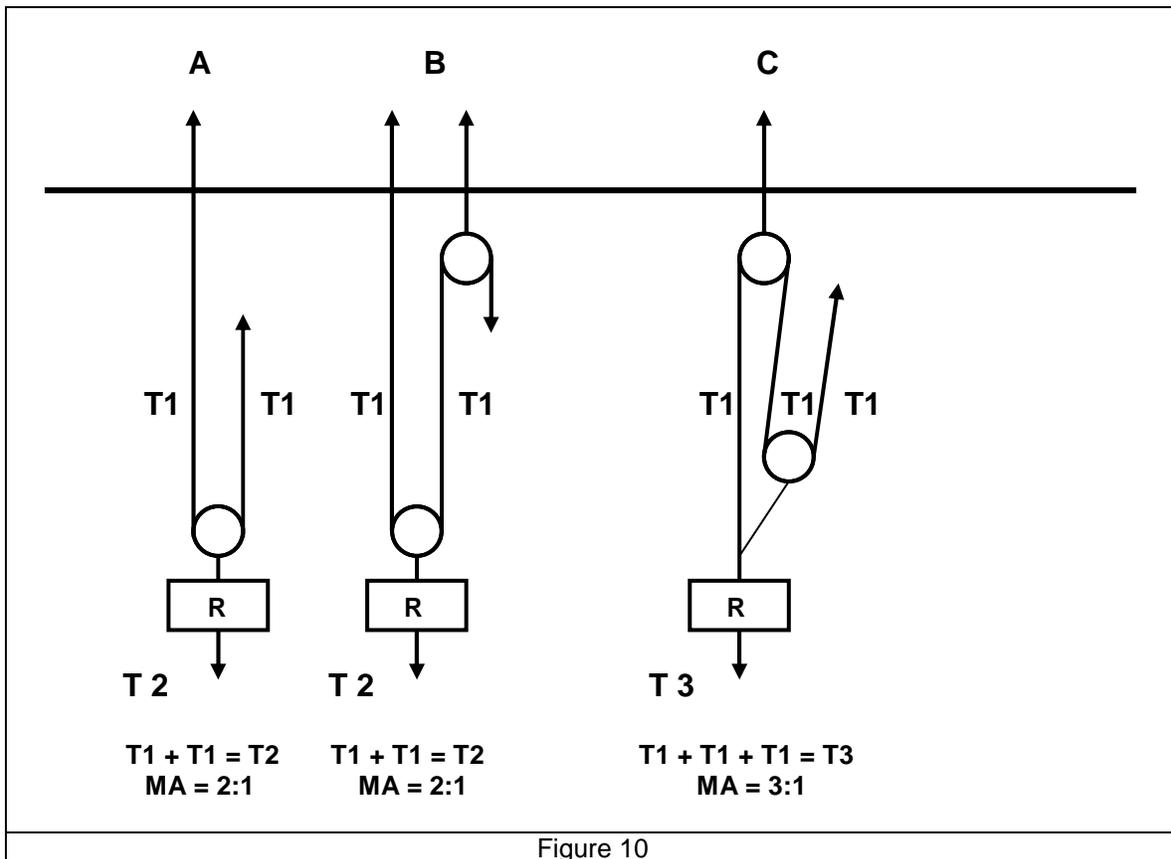


Fig. 10-A. A force of T1 is applied to the input leg on the right. It is preserved by the pulley, and persists in the supporting leg on the left. T1 + T1 gives us a T2 force applied to the pulley's point of attachment: the resistance. MA = 2:1

Fig. 10-B. This looks like a 3:1 MA, but remember, the input leg on the far right doesn't count, because it comes from a Standing Pulley. MA = 2:1

Fig. 10-C. In this case, the input leg on the far right, counts, because it is routed through a Traveling Pulley. The T1 input force is preserved by the low-friction pulleys, into all three legs, including the one on the left. The leg on the left pulls up on the resistance, the middle leg pulls up on the Traveling pulley, and so does the input leg on the right. All three are working. Thus, T1 + T1 + T1 yields a total force of T3 applied to the resistance. MA = 3:1

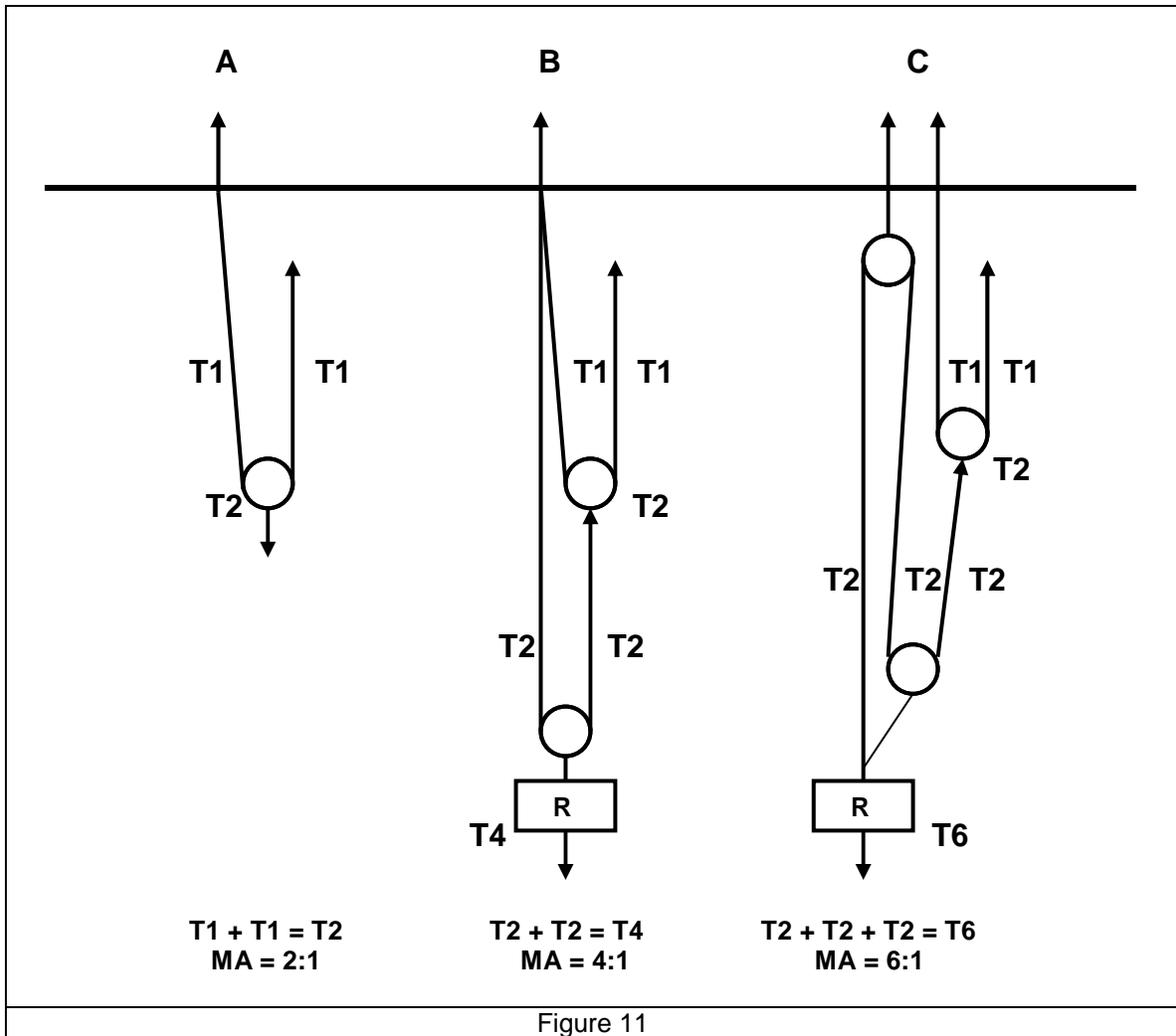


Fig. 11-A. This is the same diagram as Fig. 10-A from the previous set. It features a T1 input into the Traveling Pulley, and another T1 force transferred to the supporting leg. This set-up brings a T2 force to bear, if we attach it to some form of resistance. MA = 2:1

Fig. 11-B. On the right, in "B," we have the same rig as in "A," but instead of attaching it directly to the resistance; we piggyback it onto another 2:1 rig, and then to the resistance. Since the piggyback rig (on the right) generates a 2:1 MA, it supplies a T2 input force to the second 2:1 system. This is twice the normal input force, and the pulley preserves it in both legs. So, each leg of the second system shares a T2 force:  $T2 + T2 = T4$ . MA = 4:1

Fig. 11-C. This system begins with a 3:1 set-up, but we piggyback a 2:1 rig to its input line. The 2:1 rig brings a T2 input force to the 3:1 rig. Therefore, all three legs of the 3:1 carry a T2 force:  $T2 + T2 + T2 = T6$ . MA = 6:1

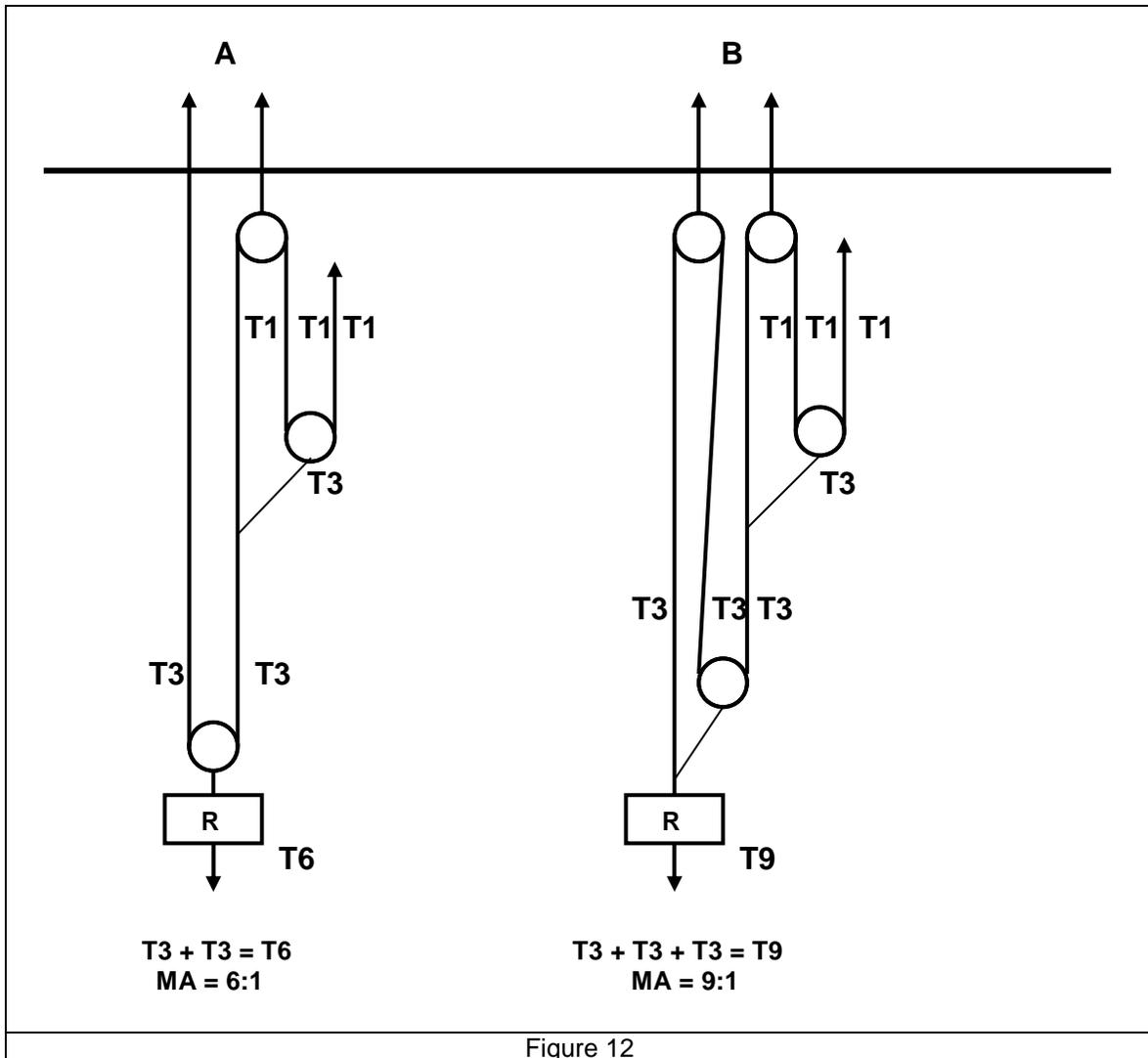


Fig. 12-A. This is a 3:1 piggybacked on a 2:1. The 3:1 carries a T1 force, on each of the three legs, for a total output of T3. The T3 force, feeds into the 2:1 system, giving it a T3 force, on each leg:  $T3 + T3 = T6$ .  $MA = 6:1$

Fig. 12-B. Finally, we have a 3:1 piggybacked onto another 3:1. The three legs of the piggybacked 3:1 on the right, combine to create a T3 force. The T3 force then loads each leg of the second 3:1 system, with a T3 force:  $T3 + T3 + T3 = T9$ .  $MA = 9:1$

### Too Much of a Good Thing

It's fun to contemplate the forces that can be generated using the systems described here. However, the reader must understand that there can be significant risks attendant to the use of these tools. Using a pulley MA system to raise the weight of a litter rig puts tremendous stress on the system, and equipment failure is a very real possibility. For this reason, it is important that we exercise caution. We must monitor the magnitudes of the forces we bring to bear. Studies have demonstrated that, when using a three wrap, 8mm., kernmantle Prusik, on 1/2" rescue rope, the main Prusik—the one closest to the load—will begin to slip at forces ranging from 7 to 9 kN (1,575 – 2,125 lb.). Armed with this knowledge, we must develop the habit delegating one rescuer to monitor that main Prusik throughout the duration of the raising operation. This person

must call a halt at the first sign of slippage, and the hauling team will cease activity until the cause of the excessive strain has been found and corrected.

## **Conclusion: The Take-Home Messages**

1. Single sheave pulleys double the input force at their point of attachment (this effect is magnified proportionately, when using multi-sheave pulleys). While this effect can make it easier to move a load, it also can increase the stress on our rigging, with potentially disastrous results. Make sure your anchor systems have sufficient strength to withstand these forces. Always perform a “white-board analysis” prior to putting your raising system to work.
2. Calculate the MA of your pulley system by counting the supporting legs, and including the free end of the rope, *if* it comes from a Traveling Pulley.
3. To calculate the MA of a piggybacked (compound) system, simply figure the MA of each individual system, and multiply the results.
4. **Monitor the stress within your system!**

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