PULLEYS & THE 3:1 PULLEY SYSTEM
2nd Revision

Based on the number of mistakes and half truths which make their way into publications it would appear that few climbers, instructors or even rescue personnel seem to be able to tell us that much about pulley systems with any degree of certainty. In June of 1982, I began compiling a battery of data on pulley systems in both a practical and theoretical sense. The result is reams of paper containing the results of this research, from which the following generalities have been drawn.

Let us start by looking at the pulley itself. What makes a good pulley? Carabiners are often used as pulleys in climbing situations. Is there any problem with this?

A good pulley is one in which most of the work we do in pulling a rope over it is not lost and can go to serve the required purpose. This is best met by having a large diameter sheave (or wheel) over which the rope runs, and by having this sheave run around a shaft with as little fiction as possible. The latter is often achieved to best effect by using some form of sealed or roller bearings. Oilite or brass bushings have been used to good effect in some designs and are occasionally referred to as brass bearings. The least effective design is called a plain bore sheave, which is simply a hole drilled through the material which forms the sheave with a shaft inserted. Even though plain bore sheaves are least effective, they are perhaps most common in utility pulleys and small pulleys for mountaineering as they are also least expensive to produce.

A good pulley protects the rope from abrasion and the rope sheath should not be pinched or abraded against the cheeks (sides) of the pulley. The pulley should be strong enough to withstand the types of loads that it will be used under and should preferably have a 5:1 *or higher* factor of safety built in. (This means it should be able to withstand at least five times more force than you anticipate loading it with.) It should be "efficient" at the types of loads it will be used under and should be capable of dissipating the heat which will build up during use. It should have as high a working efficiency as possible in practical use with varying types of rope. Pulleys for mountaineering or related rescue work are also required to be as light as possible while retaining the above qualities.

Pulleys used in mountaineering and rescue are usually of the snatch block type, which means the cheeks or sides can be split open to allow the rope to be placed inside. Other special purpose rescue pulleys for bypassing knots or minding prusiks are available.

To answer the second question, a carabiner can certainly meet some of the criteria listed above, particularly strength, but would fail in the areas of efficiency and protection of the rope. To understand how much difference can be expected by using pulleys instead of carabiners I have listed some tables of predicted performance using pulleys of varying efficiency.

The system we will look at is the popular simple pulley system employing two pulleys which has an ideal mechanical advantage of 3:1. (Ideal here refers to the absence of friction, rope elongation, inter-fiber friction, etc.) This system is occasionally inappropriately referred to as the Z-pulley system but should more properly be referred to as the "3:1 Simple Pulley System", as there are several very different systems which can have a "Z" configuration. We will compare using two carabiners with a pulley factor (sometimes called 'pulley efficiency') of 0.45 against two common rescue pulleys with a pulley factor of approximately 0.70.

Using just the carabiners and the equation that allows us to predict the performance of this system we find that we should be able to anticipate an actual mechanical advantage or more properly a "Force Advantage Ratio" of 1.65:1; while using the aforementioned pulleys we predict a Force Advantage Ratio of 2.2:1. With experimentation this has been found to be an very close approximation of the actual Force Advantage Ratios for these two sets of circumstances. But what does this mean? It means that if you had to pull up a 200 lb. weight using just carabiners, you would have to pull with a force of 121 lbs., yet with two pulleys, in this case two pulleys of only moderate efficiency, you only have to pull with a force of 91 lbs. This represents approximately a 25% reduction in the force required to raise the weight.

This is not the entire picture however, as we have not looked at another interesting facet - Efficiency. Efficiency is a ratio of the system's output to the system's input. We find that using carabiners the 3:1 system is 55% efficient while with the two moderately efficient pulleys the system is 73% efficient. You may consider this to be insignificant but let me introduce a 'good' pair of pulleys with a pulley factor of 0.85. Their force advantage ratio in this system is 2.57 and the system efficiency becomes 86%. Some pulleys can be even better!

This all seems to be very good but let us take a look at it in a more coordinated fashion. The following is a table which shows us how the Force Advantage Ratio and efficiency vary in the 3:1 Simple System. ('p' = pulley factor; CFAR = predicted or calculated force advantage ratio; 'E' = overall system efficiency; 'w' = force required to raise 200 lbs.)

'p'	**0.50**	**0.60**	**0.70**	**0.75**	**0.80**	**0.85**	**0.90**	**0.95**
CFAR	1.75	1.96	2.19	2.31	2.44	2.57	2.71	2.85
'E'	0.58	0.65	0.73	0.77	0.81	0.86	0.90	0.95
'w'	114	102	91	87	82	78	74	70

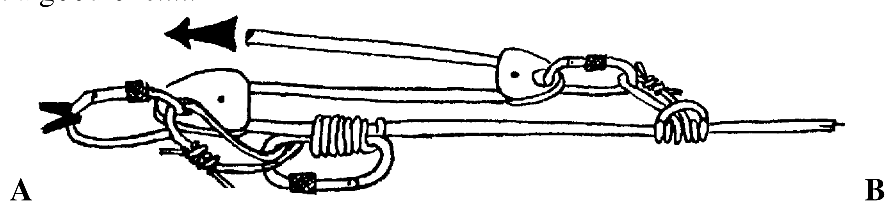
It should now be readily apparent that the use of two highly efficient pulleys can decrease the force that you must pull almost by half while ensuring that 95% of the work you do goes to raising the weight rather than being lost to friction. With carabiners you have to work almost twice as hard as you would with 95% efficient pulleys in order to raise the same weight!

How about only using one pulley? Let us look at a similar table where instead of using two pulleys of equal efficiency we use one pulley and one carabiner. The position of the pulley and carabiner are critical if you wish to maximize the Force Advantage Ratio and system efficiency. This will be discussed shortly. ('p' = pulley factor; CFAR = predicted or calculated force advantage ratio; 'E' = overall system efficiency; 'w' = force required to raise 200 lbs)

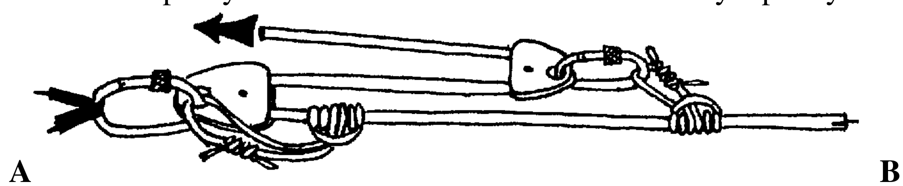
'p'	**0.50**	**0.60**	**0.70**	**0.75**	**0.80**	**0.85**	**0.90**	**0.95**
CFAR	1.71	1.85	1.99	2.07	2.14	2.21	2.28	2.35
'E'	0.57	0.62	0.66	0.69	0.71	0.74	0.76	0.78
'w'	117	108	101	97	93	90	88	85

You can see that once again we can realize excellent gains by the addition of even a single pulley into the system and the greater the efficiency of that pulley, the greater the gains. It only makes sense! The positioning of that pulley is very important as I mentioned before and you have two choices as to where you should put it. If you pick the wrong location however, the effectiveness of this single pulley is radically diminished. The following diagrams of 3:1 Simple Pulley Systems have the pulleys labeled as 'A' and 'B'. By placing the pulley at 'B' you will make optimum use of the pulley and the resulting efficiency and Force Advantage Ratio will be maximized. Similarly, if you have two pulleys, one of which is more efficient than the other, you should place the most efficient at 'B' and the least efficient at 'A'.

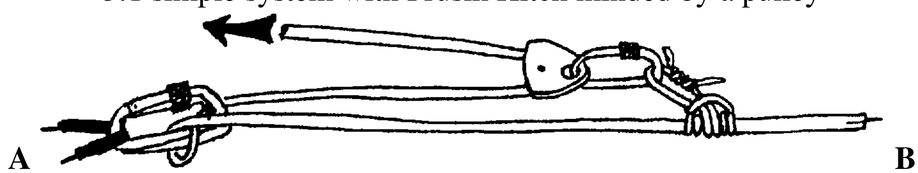
In summary, I will say that in an emergency one pulley could be worth a whole lot, so carry at least one and make it a good one.....



3:1 simple system with Bachmann Hitch minded by a pulley



3:1 simple system with Prusik Hitch minded by a pulley



3:1 simple system with Garda Hitch

Basic Reminders & Generalizations for Pulley Systems

1. Increasing the mechanical advantage of a system increases the amount of rope you have to pull, therefore use the lowest mechanical advantage of pulley system that allows you to do the job.

2. If the tied off end of the rope in a simple pulley system is attached to the load, the mechanical advantage will be an odd number; If it is on the anchor it will be an even number.

3. In simple (block and tackle style) pulley systems, friction begins to win over mechanical advantage once you go to systems above 5:1 or 6:1. In situations where higher mechanical advantage is absolutely necessary, try compound or complex systems instead.

4. A compound system will often be more efficient than a simple system with the same mechanical advantage, but the compound system may require much more frequent resets.

5. If the last pulley in a system (on the haul team end of the pulley system) is attached to the anchor then it only serves to change the direction of the pull and does not add to the mechanical advantage.

6. In simple systems, the number of strands of rope directly support the load are added up to give the mechanical advantage. A strand of rope coming from the haul team to a pulley attached to the anchor is not added to the total.

7. In compound systems, but not complex systems, the mechanical advantage of the system is determined by multiplying the mechanical advantage of the component systems. (Compound systems are those in which one simple system pulls directly on the end of another simple system.)

8. A compound system will require resetting less often if the system with the higher mechanical advantage pulls on the system with the lower mechanical advantage.

9. Friction outside the pulley system can increase your work just as much or more than friction inside the pulley system.