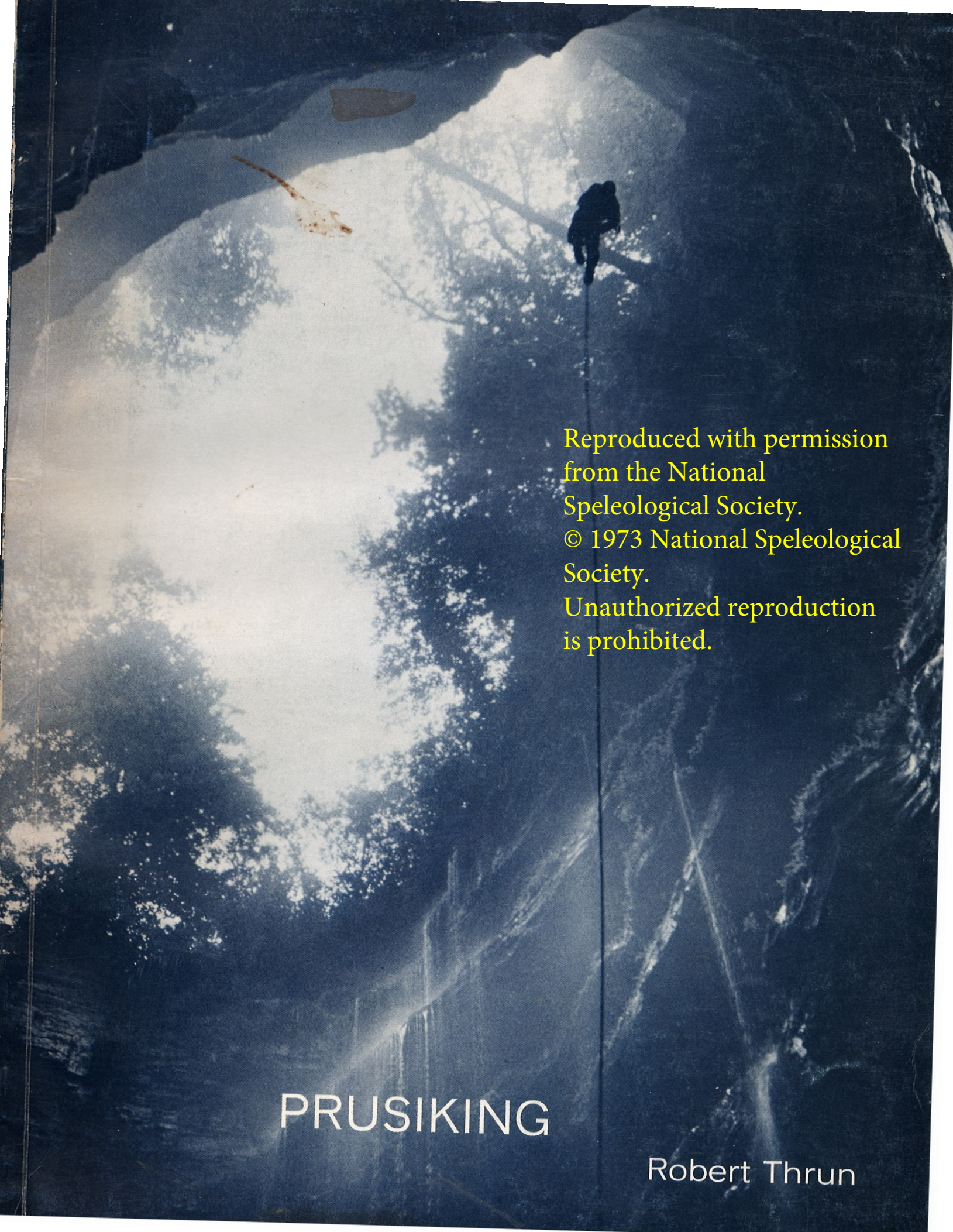

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PRUSIKING

Robert Thrun

PRUSIKING

by Robert Thrun

National Speleological Society
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Huntsville, Alabama 35810
USA

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AUTHOR'S NOTES

When I started caving, I wanted a comprehensive source of information on techniques. There was some information on prusiking in print, but most had to be learned by personal contact and experience. I decided that some of the knowledge gained should be put into print. This is the article I wanted to find when I was beginning caving.

I do not claim to be the world's greatest prusiker--simply an experimenter, observer, and collector of information. I have tried to represent fairly all the techniques I have heard of.

Because I have tried to be comprehensive, the text includes a great deal of information on techniques of all degrees of usefulness. This sort of thoroughness is of greatest value to the experimenter. Inevitably this chapter will be picked up by someone who simply wants to learn to prusik. I advise the beginner to read the sections on Beginning and Training, and Popularity before any others, and to skip around within the rest of the text as indicated by these two sections.

Robert Thrun
1971

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Special Publications are irregular publications of the National Speleological Society (NSS). The series will cover cave related topics which are generally too large to be included in the regular Society publications, the *News* and the *Bulletin*. Publication will occur as topics and funds are available.

Papers, including thesis, are invited on topics such as major cave systems, extensive work on a given cave, biological topics and discussions of equipment and/or techniques.

Potential authors should contact the Coordination Editor via the NSS Headquarters.

Allan P. Haarr
1973

PREFACE

This monograph is being published by the National Speleological Society as part of the Society's purposes to "advance in any and all ways the study and science of speleology". Speleology here includes not only knowledge of caves but of cave exploring techniques and especially in this regard safety in cave exploring and the protection of the unique features of caves by good conservation practices.

The development of "vertical technique" has, in the past few years, greatly expanded our knowledge of new and old cave systems by providing a safe and efficient method to surmount what were previously major obstacles - pits of great depth. Beyond the purposes of new exploration, however, "vertical caving" has become a pleasure in its own right, providing the exhileration of descending and ascending through great subterranean voids as well as the more mundane, but nevertheless exciting, competition of "prusik racing".

Where once pits were ascended by brute force (direct hauling) or by ladders, with the attendent complexity of belay lines, signals, and heavy equipment, the new techniques have liberated both the individual and the activity, reducing the equipment and effort involved but replacing these with the need for increased knowledge and skill. This publication is part of the effort of the National Speleological Society to disseminate such knowledge for both increases ability and safety in cave exploration.

Bob Thrun is well aware that written descriptions cannot replace learning from an experienced teacher combined with practice and personal experience, and states this clearly. While local instruction is essential, it does tend to emphasize the meathods preferred by the instructors or which appear most suitable for the local caves. However all such developments can gain from a cross-fertilization of ideas and this work, by bringing together an extensive comparison of equipment and techniques, serves this purpose. We hope that there *will* be argument about the author's opinions and preferences – and that therefrom will come yet further advances.

A word to the beginner: this work does not represent all that needs to be known to safely undertake ascents by one or another method of "prusiking". It is assumed that you have learned most other caving techniques already and know about clothing and lighting and safety in exploring and knots and a host of other things. Also, the beginner is likely to be confused by the plethora of alternatives described and, without guidance, not know where to begin. Bob Thrun's answer, and I strongly concur, is *learn to climb with knots first.* When all else fails, knots can be improvised and made to work so long as the main rope is in place!

And a word to the advanced "vertical caver": you will say that this work is out of date – and it is; any such attempt as this would be in an area of techniques developing and changing as rapidly as this one. Look upon this work as capturing, in as thorough a fashion as is now useful, a moment in the improvement of speleological techniques. Above all, contribute to the dialogue that is leading to better methods by writing about *yours*, demonstrating it at NSS Conventions, and teaching the *safe* use of *proven* techniques to the newcomers.

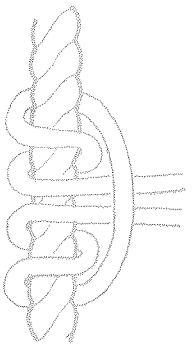
Besides being useful and enjoyable, prusiking (and descending methods) come as close as anything to the ideal means of traversing a cave without damage to that delicate environment – *flying*. But these techniques also make it easier to enter previously nearly inaccessible cave passages, and thereby to increase the "caving pressure" upon the cave environment and its beauty, interest in native organisms. For those who have not previously encountered the principles of the National Speleological Society in this regard, and as a reminder to those who have, let me reiterate that caves come as close as anything that is known in this world to being natural *living museums*, and any damage or alteration is to be avoided. Life forms found in caves (bats, fish, crayfish, insects, etc.) should not be disturbed or killed; nothing should be left in a cave; nothing should be removed. Leave caves in a condition that all future generations can experience them as they were when first seen by the cave explorers of today – a goal worthy of all the effort we otherwise devote to improved equiptment and techniques.

Rane L. Curl, President
National Speleological Society



PRUSIKING

by Robert Thrum



INTRODUCTION

Prusiking is the most popular method in the United States for ascending from deep pits. It has eclipsed the older cable-ladder and block-and-tackle methods, and has now been developed to a fine art. Prior to the publication of the original version (Thrun, 1967) of this article, the amount of printed information did not adequately reflect the high degree to which prusiking had developed. Very few people have written more than a general description of their personal techniques. There have been some notable exceptions. It is rather remarkable that about as much writing on the subject of prusiking comes from areas with few deep pits as from the areas with many.

Prusiking is a means of climbing a standing or fixed rope. The standing rope is gripped by a climbing knot, made of rope, or by some sort of mechanical rope-gripping device. All of these will grip the standing rope when a downward pull is put on them. When the tension is released, they can be loosened and slid up the standing rope. Either two or three knots are commonly used. They are connected by short slings to the body and feet. By alternately putting weight on the knots and moving them upward, a person is able to climb a rope.

Prusiking owes its birth and name to Dr. Karl Prusik of Austria, who first described how the knot that now bears his name could be used for climbing a rope (Prusik, 1931).

The knot was not entirely new. Similar sliding hitches had been used before in other applications, but it was Prusik who inspired later mountain climbers and cavers. His name has, by common usage, lost its capitalization and become successively an adjective, an adverb, a verb, and a noun.

Prusiking as a routine technique for ascending out of pits has been in use since 1952 (Quinlan, 1968). In the early years only "Vertical Bill" Cuddington of Virginia used this technique extensively. Quite often only the landowner stood by on the surface. With this lack of support, Cuddington did not explore the passages at the bottom of a pit, which helped gain him a reputation for disliking horizontal caves. There are some passing references to the technique in Europe in the 1930's, but prusiking did not become popular there. The number of persons using rappel-prusik techniques grew slowly at first. (The general method must be referred to as rappel-prusik because the rappel is equally essential for convenience.) In the late 50's and early 60's there was a general conversion from ladders to rappel-prusik methods. This changeover was in the face of strong criticism, mostly on the grounds of safety, partly on the speed or the difficulty of learning. The changeover cannot be precisely dated because it was gradually done by various groups and individuals. There are still some individuals who use ladders. Even good prusikers occasionally use ladders, mostly for short drops.

The main reason for the changeover was convenience, which is manifest in various ways. The need for topside parties to handle safety lines is eliminated. The equipment weighs about one-fourth as much as ladders and their safety ropes. Rope handling, with its effort, danger of dislodging rocks, fouling, and the need for very good communications is minimized. Anyone who has explored deep pits by rappel-prusik techniques can easily imagine the greater total effort of using ladders. The reverse is not true, and prusiking has spread mainly by demonstration.

The prusik system consists of the mechanical components and the techniques for using them. The skill and strength of the individual play a large part in the overall effectiveness of the system. Because of this, there is no single "best" system.

The climbing knot or mechanical ascender forms the heart of any prusik system. A lot of devices have been tried and can be divided into three classes: rope knots (technically these are all hitches), semi-mechanical knots, and mechanical ascenders. The semi-mechanical knots use rope as the main gripping part of the knot and have a metal part, usually a carabiner, to facilitate loosening the knot. In prusik races they have been classified both as knots and as mechanical ascenders. The knots and devices to be considered are:

Knots consisting entirely of rope

1. Prusik knot
2. French prusik
3. Hedden knot
4. Spong knot
5. Helical knot
6. Hitch series (escape knots)
7. Other

Semi-mechanical knots

1. Bachmann knot
1. rbs knot
3. Carabiner prusik
4. V-knot
5. H-bar knot
6. Eight-link knot
7. Hedden eight-link knot
8. Snap-link twist
9. Other

Mechanical ascenders

1. Jumar ascenders
2. Roloff ascenders
3. Heibler rope clamps
4. Climbing cams
5. French ascender
6. Warden ascender
7. Motorized ascenders
8. Other

(The "Other" are un-named or untried devices that might work well. They are especially numerous in the mechanical ascender category.)

KNOTS CONSISTING ENTIRELY OF ROPE

Prusik Knot. The prusik knot was the original climbing knot and is still the standard to which new knots and ascenders are compared. It is used by both beginners and experts. The usual form and the method of tying it are shown in Figures 1 through 3.

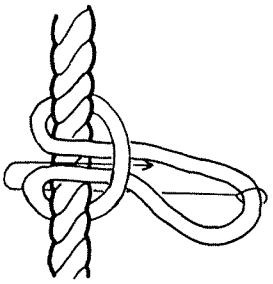


Fig. 1. Start a prusik knot with a ring hitch.

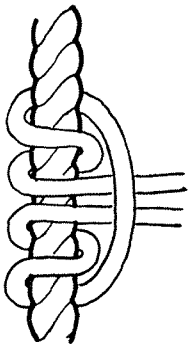


Fig. 2. Tuck the sling through the knot a second time to give four coils.

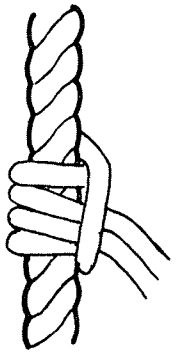


Fig. 3. The finished knot when pulled tight. This is a right-handed knot.

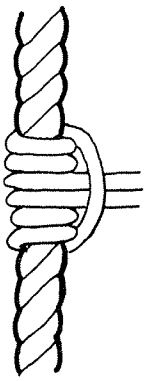


Fig. 4. 6-coil prusik knot.

Sometimes, under wet or extremely muddy conditions, the sling is passed through a third time to form a 6-coil prusik knot (Figure 4) which holds better. I prefer to call the knot by the number of coils it has rather than by the number of times the sling is passed through its bight because it is possible to tie a prusik knot with an odd number of coils. More coils in the top of the knot make it hold better against a downward pull and also make it move upward more easily.

To tie a 3-coil prusik knot (Figure 5) you must have the end of the standing rope available or retie the prusik sling after tying the prusik knot.

The form of the knots in the diagrams of Figures 4 and 5 are called rightside-up or right-handed prusik knots. The knot shown in Figure 6 is an upside-down or left-handed prusik knot.



Fig. 5. 3-coil prusik knot.

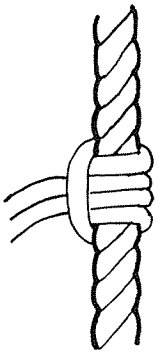


Fig. 6. Left-handed prusik knot on right-handed rope.

Many writers issue dire warnings against tying the left-handed knot because its holding power is less. This advice is correct if the knot has marginal holding power. If the knot holds well, it will be found that the left-handed knot is easier to move. Some people tie the top knot left-handed and the bottom one right-handed to minimize rope twisting. The greater holding power of the right-handed knot seems to result from the turns in the upper part of the knot catching on the spiral lay of the rope. The right-handed knot holds better only on right-hand laid rope, with the strands as shown in Figure 3. On braided rope

the orientation of the knot does not matter. If, by some circumstance, you should come across a left-hand laid rope, a left-handed knot would hold better.

There have been very few tests made of the holding power of knots. Gibbs and Doll (1969) found that a four-coil prusik knot would slip at 450 pounds. They used 5/16" Goldline slings on a 7/16" Goldline and a 1/2" braided main line. At 1600 pounds the sling broke at the prusik knot. I do not regard Goldline as a very good sling material, based on some tests of my own. A four-coil knot tied with 3/8" laid polypropylene on a 7/16" laid nylon rope slipped at 700 pounds. A three-coil knot tied with 1/4" laid polypropylene held and broke at 900 pounds. Penberthy (1969) tried 1/4" dacron on a 7/16" manila standing line. The manila broke at 1000 pounds. Again, this is an unusual combination. A good bit of work needs to be done to find the strength of prusik knots, but experience has shown the strength to be adequate for ordinary ascending needs.

Most beginners loosen the knot by pushing on the bight connecting the upper and lower parts of the knot. I have seen one person use a loop of a lightweight cord inserted through the knot at that point as an aid to loosening it. This was effective but required an extra motion to tug on the cord. Pushing the doubled rope into the knot to introduce some slack seems to be more effective in loosening the knot. Bob Smith (1964) recommends tying an overhand knot in the doubled rope about 2 inches from the prusik knot as an aid to loosening it. He says the overhand knot helps in keeping more tension on the bottom strand than on the top one.

I use various means to loosen my prusik knots. Although I am not yet very proficient I can see how, with practice, a person may loosen and move the knots in one motion so that an onlooker thinks he is using some rope combination that needs no loosening. I use the following method, with no knots in the sling rope: I grasp the doubled sling rope with the third and fourth fingers and lift and twist my hand as if the sling were a pump handle pivoted at the prusik knot. This puts slack into the top of the knot. Ideally, this alone will loosen the knot. Most of the time, additional tricks are necessary, such as pushing the double strands into the knot. The thumb and first two fingers are free to manipulate the knot in various ways. Pressure may be put on the bight if desired. The double strands can be wrapped further around the standing rope, away from the restraining bight. Often the coils of the tightened knot are slightly separated, and by squeezing them together, slack can be put into the knot. The separation can be deliberately put in by holding the coils apart when tension is applied to the knot.

Each person probably has his own combination of loosening motions, some of them done unconsciously but acquired as the result of practice. Most knots require more than one motion to loosen them, and some jammed knots will need the use of both hands to move them. A number of factors--diameter of sling rope, number of coils, tension on the main rope, and orientation of knot--trade holding power for ease of movement. Mud and water conditions reduce both.

Often the advice is given not to grab the prusik knots since this will make them slip. This depends on the margin of holding power of the knot. My knots don't slip, even when I want to change from prusik to rappel.

French Prusik Knot. The French prusik knot (Figure 7) is apparently one of the older climbing knots, although I have never seen its use described in print. Plummer (1963) included it in his analysis. As a method of hitching to a pole, it is old and well known. It is tied

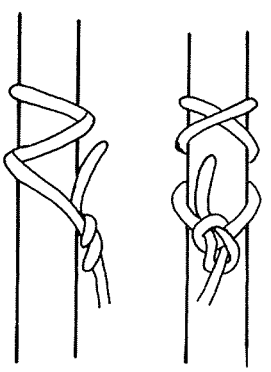


Fig. 7. French prusik knot.

by wrapping one end around the standing rope, with the end tucked under at every other crossing so that the rope crossings alternate. Otherwise, a distorted helical knot is obtained, which may hold just as well but is a different knot. The French prusik knot is finished by tying the end to the sling rope. A bowline is probably the best knot for this purpose. Unfortunately, there is no room for half-hitches in the usual manner, although the end of the rope can be hitched around the sling running from the knot to the prusiker's body, or a knot can be tied in the loose end to keep it from slipping through the bowline. The French prusik knot, when properly tied, is easy to loosen by simply pushing on the bottom of the knot. The amount of slack in the knot is critical--too much slack will cause the knot to slip; if it is too tight, it is hard to move. Only experience can tell you how much slack is proper. The knot will loosen up after a short use as the bowline is drawn tight and the coils distribute themselves. It can be made to hold under adverse conditions by using more turns. The French prusik knot has an advantage when used as a prusik while rappelling or when changing from prusik to rappel. It can be loosened under tension by pushing down on the uppermost loop. The two main disadvantages of the French prusik knot are: (1) it takes a long time to tie and adjust; and (2) the knot elongates when force is put on it, causing the prusiker to lose a bit of distance on each step. A self-adjusting knot can be tied with the end of a doubled sling rope, but this soon tightens itself to the point where it is hard to move.

Hedden Knot. The Hedden knot is tied as shown in Figure 8. The form shown in Figure 9 has an extra twist that causes the knot to bind. Figure 10 is an upside-down knot that will slip, because the knot is directional in its holding ability. Many of the motions that are used for loosening the prusik knot can be used with this knot. Smith's tests (1964) show that this knot is harder to loosen than the prusik knot. Limited experience indicates that the Hedden knot is about as good as, or slightly inferior to, the prusik knot.

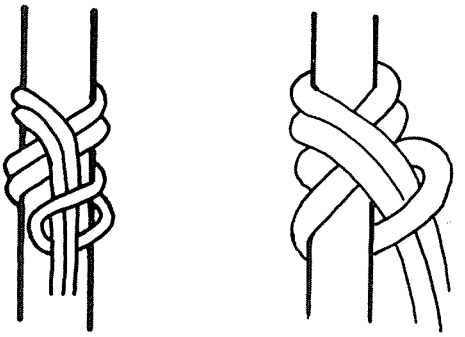


Fig. 8. Hedden Knot. Two views of Hedden knot. The two knots are tied in an identical manner with different size slings.

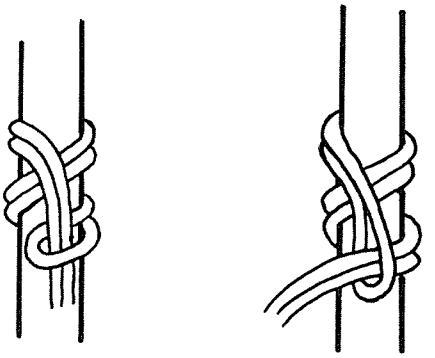


Fig. 9. Hedden knot with twist.

Fig. 10. Upside-down Hedden knot.

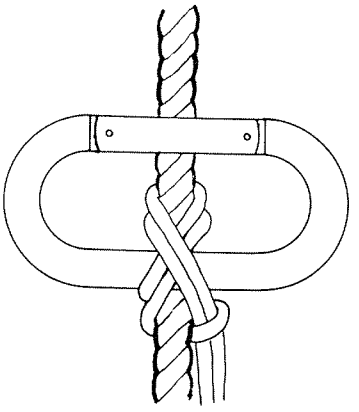


Fig. 11. Hedden knot with carabiner.

Chet Hedden (1959) recommends putting a carabiner through the knot as illustrated in Figure 11 for loosening the knot if it is very hard to move. Most of the time it will not be necessary to do this.

Spong Knot. I consider the Spong knot to be a monstrosity, and include it for the record only. Figure 12 illustrates the steps in tying this knot. It is difficult to tie, jams most of the time, slips some of the time, and binds upon itself instead of upon the standing rope. It is directional in holding ability because of the two coils in the upper part and one coil in the lower part. Under some circumstances it might move as easily as claimed by its originator (Spong, 1962), but I can't imagine these circumstances. The endorsement of the Spong knot by Dwight Deal (1966) caused me to retest it. I still consider it to be the worst ascending knot of all. Bob Smith's tests (1964) give the same result as mine.

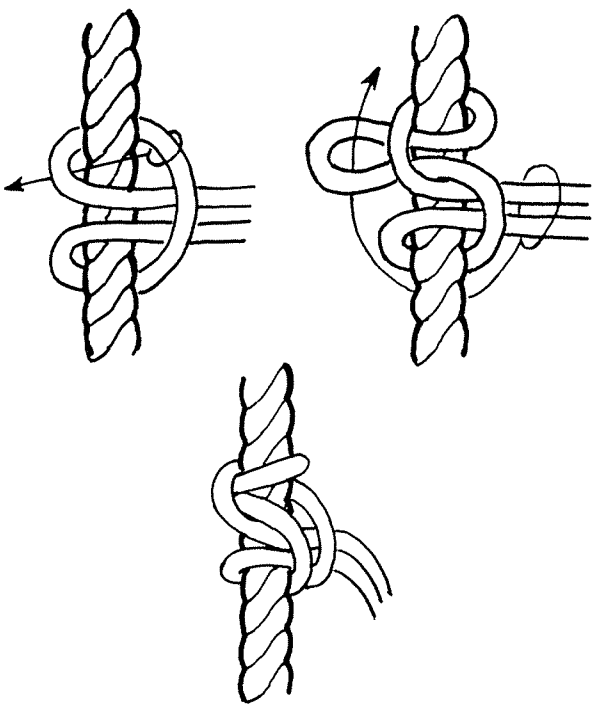


Fig. 12. Steps in tying the Spong knot.

Helical Knot. The helical knot, Figure 13, was invented by Clarence Cook and Tony Marchi (Cook, 1961; Cook and Marchi, 1961). It is about as open as a climbing knot can be. By my observation, the force is applied to the top of the knot. For this reason I recommend tying it by winding the free end downward. Penberthy (1969) has observed the opposite and ties the knot by winding upward. Tie it, and judge for yourself. It holds better if wound in the same direction as the lay of the standing rope.

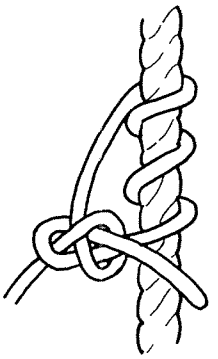


Fig. 13. Helical knot.

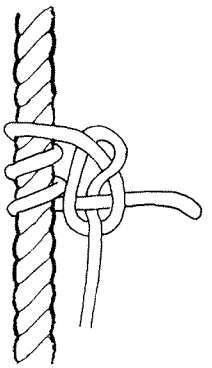


Fig. 14. One way of finishing and sizing helical knot.

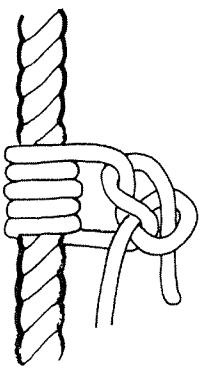


Fig. 15. The finishing knot used by Penbertby and Mitchell (not a bowline).

The knot shown for finishing off the helical climbing knot is structurally the same as the bowline, sheet bend, and becket hitch, but has the forces applied to it in yet another fashion. The quickest way of tying the bow-

line and adjusting the amount of slack is shown in Figure 14. It can be secured with half hitches below the knot. The simple bowline is the most common way of finishing off the helical knot. Mitchell (1966) and Penberthy (1969) use a distorted bowline (Figure 15).

Like the French prusik knot, the helical knot must be adjusted for an optimum amount of slack. Too much slack and the knot slips; too little slack and it is hard to move. The helical knot does not elongate as much as the French prusik knot when weight is applied. The helical knot can hold with more slack in it than a French prusik can tolerate. If the turns of a helical knot are distorted to resemble a French prusik knot, it will not hold as well as it does in helical form.

When the helical knot was first introduced, Plummer (1961) evaluated it, saying that it does not work with some rope-size combinations, that it is insecure because of the finishing sheet bend, and that it may slip if the turns cross each other. With this sort of introduction (Plummer's critique was printed immediately under the article by Cook and Marchi) the helical knot did not become popular.

A few cavers, not knowing how bad the knot was supposed to be, have used it with good results. Penberthy rediscovered the helical knot independently and called it the "P-H knot," inspiring Mitchell (1969) and Graham (1969), who used the term "ascender knot." Penberthy and Mitchell used five turns. Graham used three. Both the number of turns and the amount of slack must be adjusted to suit the person's weight and the combination of rope diameters and material used. It takes a bit of experimenting to determine the proper adjustment.

Hitch Series. A number of slightly different climbing knots can be tied with a series of hitches (the basic ones are shown in Figure 16). The top hitch is universally called a half hitch. The others are almost nameless (they could be correctly described by the unwieldy names of "round turn half hitch" and "two round turn half hitch") and are only parts of more elaborate hitches. Two or more hitches are tied about the standing rope, using the free end of the prusik sling rope. The top end of the rope is left free. Some combinations have names, such as the magnus hitch and rolling hitch.

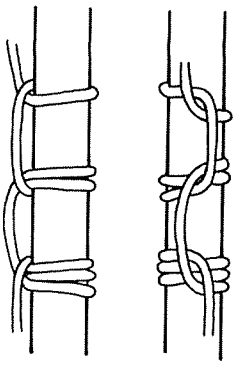


Fig. 16. Basic hitches.

Plummer (1966) has termed the hitch series "escape knots," recommending them for use when all other climbing knots fail to hold. Each hitch is a force multiplying device. The gripping power of a series is dependent on the product of the force multiplying ratios of the hitches in the series. The topmost hitch has a slight amount of drag due to snubbing and stiffness of the rope.

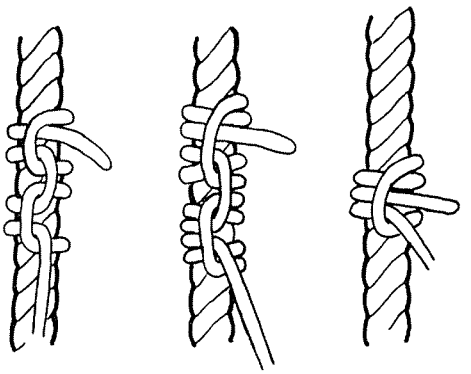


Fig. 17. Hitch series.

A hitch series (Figure 17) can be made to hold on any rope by adding hitches. In other words, if a series starts to slip while prusiking, pull up on the free end to stop the slipping and tie more hitches with that end. If the series is holding well and is hard to move, some hitches may be untied. Of course,

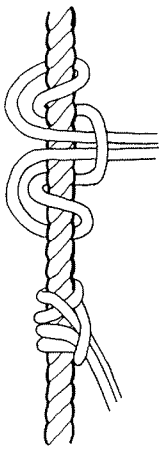


Fig. 18.

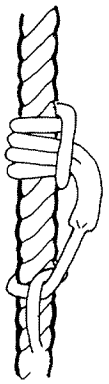


Fig. 19.

the shorter the series, the easier it is to move. To make it easy to loosen a long series, the hitches should not be jammed together. The only slack for loosening them comes from the rope in between the hitches. On the other hand, too much slack will mean the series will elongate when tightened. You can change from prusik to rappel by untying the hitches--even under a little tension. The sling rope will tend to roll if the hitches are tied in the same direction; therefore, they should be tied in alternating directions. There will be some slippage of the sling rope through the hitches during use, but not enough to be dangerous if the ends are sufficiently long.

Other Knots. The knot in Figure 18 requires only one tuck to tie it. It looks like a distorted prusik knot that cannot be manipulated into prusik form, and appears to bind upon itself. I have not tested it but suspect that it is not as good as the prusik knot in ease of loosening and holding power.

One way of increasing the holding power of a knot is to tie a half hitch with the sling rope as shown in Figure 19. This is particularly useful if the knot is tied with a small eye splice. It drastically changes the sling lengths and makes prusiking awkward.

SEMI-MECHANICAL KNOTS

The semi-mechanical knots use the sling rope to do most of the gripping. They have a metal part to facilitate loosening–a carabiner being the most commonly used object, although I have seen descending rings used because of their light weight. Locking carabiners are more often used because the loosening motion could open the gate of a non-locking carabiner. These carabiners might be used for a three-carabiner rappel.

Although it is a matter of considerable controversy, the Bachmann and rbs knots appear to be inferior to the prusik knot in their holding power on muddy ropes. The proponents of any particular knot will testify how well their knot works on the muddiest drop they have encountered, which may or may not have been really bad. The holding power varies with many factors, so a comparison is hard to make. The prusik, rbs, and Bachmann knots all hold in most situations, although I have heard more reports of an rbs or a Bachmann knot slipping while a prusik knot held than the other way around. Of course, the holding power of any knot can be increased by taking additional turns around the standing rope.

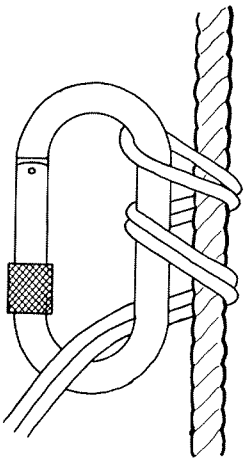


Fig. 20. Bachmann knot.

Bachmann Knot. The Bachmann knot (Figure 20) is the oldest of the semi-mechanical knots. To tie it, a carabiner is passed through a loop of sling rope. Wrap the doubled sling rope around both carabiner and standing rope. Each time around the sling is put through the carabiner gate. If tied upside-down, this knot slips and jams.

The carabiner is not, as it may appear to be, a handle. If the carabiner is pulled downward, the knot will slip. If an attempt is made to raise the knot by pulling up on the carabiner, the coils will squeeze together and the knot will jam. Most users of the Bachmann knot make no attempt to maintain any particular orientation of the carabiner with respect to the rope. Depending on the combination of ropes and carabiner, the carabiner will assume up to a 45° angle with respect to the standing rope. Other users, noting that the Bachmann knot kinks the standing rope while gripping it, emphasize the kinking action. (All the climbing knots kink the rope to some extent.) They turn the carabiner into the standing rope so that the standing rope passes through the center of the carabiner

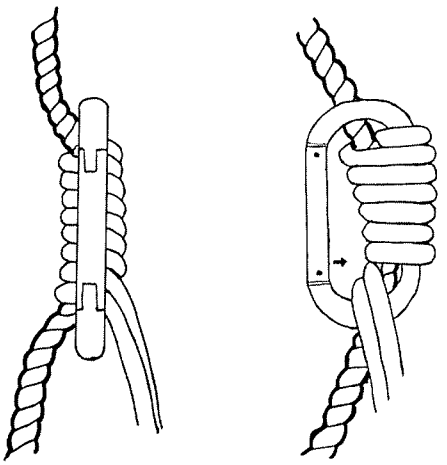


Fig. 21. An alternate way of orienting the Bachmann knot.

(Figure 21). It is claimed that this increases the holding power of the knot. In either case, the knot is raised by grasping the sling just below the carabiner and pushing on the bottom of the carabiner.

Either two, three, or four wraps of the sling around the standing rope and carabiner may be used. If a knot starts to slip, turns can be added to it without unfastening the sling: Push slack through the knot, pull the carabiner around the standing rope, and snap the sling through the gate of the carabiner.

The Bachmann knot holds better with smaller diameter carabiners and works with a wide variety of ropes, even with nylon webbing. There are two hazards to beware of when using it, however: (1) the knot can be turned upside-down without untying it merely by rearranging the coils; and (2) if the knot is left unattended with no tension on the sling rope, the weight of the carabiner can cause it to fall.

The rbs Knot. The rbs knot (pronounced "arbs") was invented by Richard B. Schroeder (1963, 1966). It is the most popular of the semi-mechanical knots and is shown in Figures 22 and 23. The two figures show identical knots, but Figure 23 better shows the method of tying. The form shown in Figure 22 is fine for saving a couple of square inches of space on a page and may be enjoyed by Chinese puzzle fans. It was the form used in the original article on this knot, and everyone else has copied it. About the only person with no copycat tendencies was Plummer (1964) who showed the knot the way it actually appears on the rope, which is just as confusing. This knot distorts into many forms while being used, all of which seem to hold equally well. To loosen it, grab the sling rope a few inches below the knot with the last two fingers. In one motion, the sling is pushed up through the carabiner while the carabiner is raised with the thumb and first two fingers. Smith (1964) found the rbs knot loosened almost instantly with a variety of sling materials. Each time the knot is set, more slack is pulled out of it than from most other knots. It is claimed that this is compensated for by ease of movement. A locking carabiner is very strongly recommended because the carabiner is so often pushed against. Even the gate of a locking carabiner has been known to come open after friction against the rope has unscrewed the safety sleeve. The rbs knot has the unusual hazard of being too easy to move. If the knot is raised and is not pulled tight, the weight of the carabiner may cause it to fall. It should be thrown upward vigorously and locked with a snap. It is not suitable for use as an automatic emergency brake while rappelling. (Both the purpose and effectiveness of a prusik safety are subjects of considerable debate.) Another problem is that if a foot sling falls, the standing rope must be pulled up with the rbs knot. This may be difficult while prusiking with two people on a rope. The rbs knot can be tied quickly without detaching the slings from the

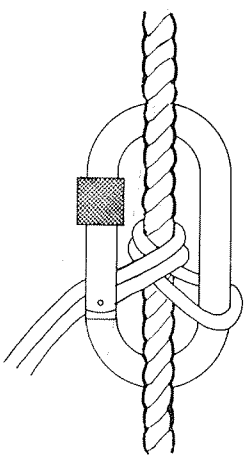


Fig. 22. A common, but confusing way of drawing the rbs. knot.

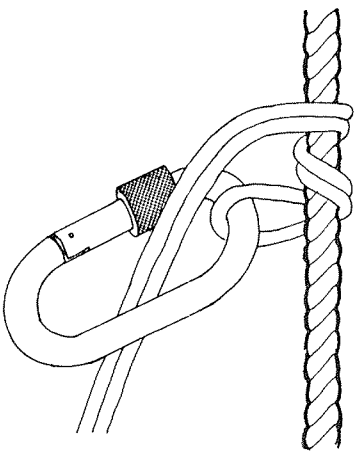
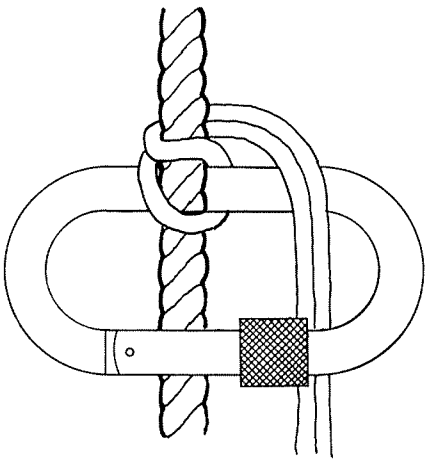


Fig. 23. This drawing shows the same knot as Fig. 22.

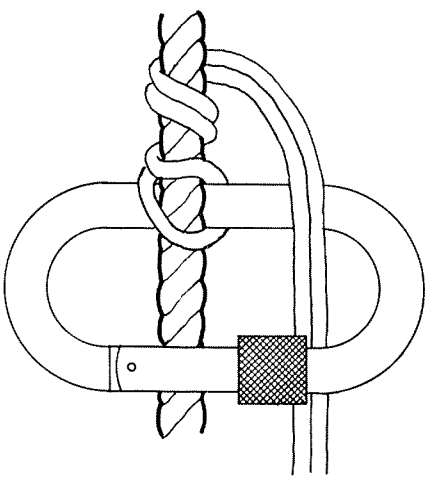
body or feet, which could be very handy for going over break-overs (protruding ledges that support some or most of the weight of the standing rope and prusiker). The possible speed of tying this knot is most valuable for ascending a series of short drops.

The Carabiner Prusik. The carabiner prusik (Figure 24) was described by Dan Meier (1964). The knot can hold with just one turn (1/4" slings on 7/16" rope) under dry conditions. Meier cautions to keep the carabiner in a horizontal position, or the knot will lose some of its holding power. I can find no cause for this to happen. Close examination reveals the carabiner prusik to be similar to the rbs knot. The carabiner prusik, however, is wrapped around the standing rope an additional half turn and so should have slightly more holding power. Most of the statements about the rbs knot also apply to this knot. Meier recommends that the sling be wrapped around the standing rope in a direction contrary to the lay of the rope for greater holding power.

The V Knot. The V knot, or Varnedoe grip knot (Figure 25), was invented by Bill Varnedoe (1965). It uses snap hooks, available at most hardware stores. The snap should be upward so the fingers do not open it when moving the knot. A double-strand version of the V knot would be an inverted rbs knot. Varnedoe claims that it works very well, but I have apprehensions about both the security



One turn



Two turns

Fig. 24. The carabiner prusik.

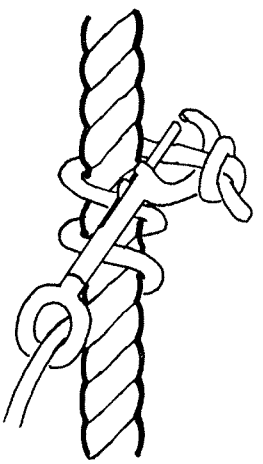


Fig. 25. The V knot.

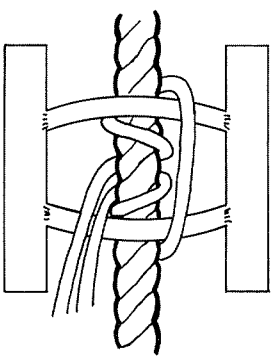


Fig. 26. H-Bar knot.

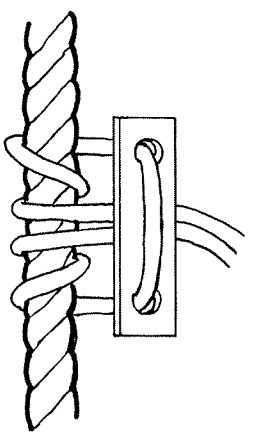


Fig. 27. Another semi-mechanical version of the prusik knot.

and the strength of the snap hook and would recommend a metal piece with two holes drilled in it instead of the snap. In fairness, however, it is true that little stress is applied to the snap hook in using this knot.

The H-Bar Knot. The H-bar knot (Figure 26), a recent development in climbing knots, is a semi-mechanical version of a prusik knot. The apparatus, which must be specially made, consists of two pieces of tubing with cross-pieces welded between them. Those who use this knot say that it works best with stiff rope slings. The purpose of the tubing legs is to keep the bight of the sling rope from slipping off the crossbars.

When I saw that a semi-mechanical version of a prusik knot was possible, many other versions immediately suggested themselves. One of the simplest of these is shown in Figure 27. Since the spacing of the crossbars affects the performance of the H-bar knot, I would suggest some experimentation to determine the optimum spacing.

Eight-Link Knot. Finding the V-knot somewhat difficult to loosen and dubious about the strength of the dog-chain snap it uses, Gerald Wood (1967) invented this climbing knot, using a figure-eight chain connecting link (Figure 28). The figure-eight links are sold in most hardware stores. The eight-link knot is a single-strand version of the rbs knot and behaves somewhat the same. The manufacturers publish no strength figures for the links, but they are quite sturdy. The links have no locking mechanism, but when I tried to make one come apart by moving the knot, the link was pushed shut no matter how I pushed on the knot. This observation should be checked before the knot is used. The links can be opened if given just the right twist. The eye through which the bight of the sling passes in the eight-link knot is much smaller, however, than the opening in a carabiner, and the eight-link knot does not always move as freely as an rbs knot.

Hedden Eight-Link Knot. William Greenwald (1968), inspired by the eight-link knot and a description of other knots, invented this one (Figure 29). It is of the same form as the Hedden knot but uses a figure-eight link as an aid for loosening. It can be loosened easily, though the method is rather unusual. The eight-link is pulled down, which distorts the knot and puts some slack into it, and then the whole assembly is pushed up.

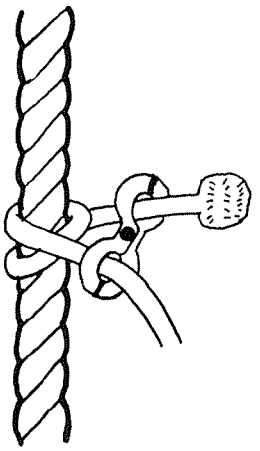


Fig. 28. 8-Link Knot.

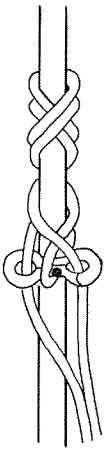


Fig. 29. Heddon 8-Link Knot.

Snap-Link Twist. After a drawing, by John Menear, of the "snap link twist" appeared in the *NSS News* (Menear, 1966), it was incorrectly identified as a Bachmann knot by two experienced cavers who did not look at Menear's drawing closely--Newson (1967), Deal (1967). I made the same mistake and did not realize the difference until Menear himself said that they were different. The snap-link twist has the standing rope and sling rope running through the carabiner while only the sling rope goes through the carabiner on a Bachmann knot. Figure 30 shows the knot the same way as Menear's drawing did, with three turns taken around the carabiner and standing rope by the sling. The knot will still hold if only two turns are used and will even hold with one turn if the proper sling rope is used and the knot is *very* carefully set by hand. I do not recommend the one-turn knot, but the two turn knot seems to have adequate holding power. The one-turn knot is shown for the purpose of comparing knot structures (Figure 31). When properly oriented, it resembles the

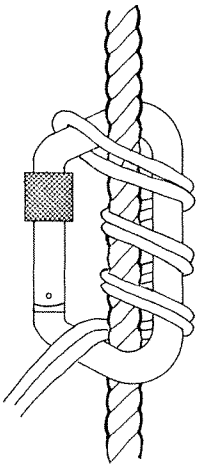


Fig. 30. Snap Link Twist.

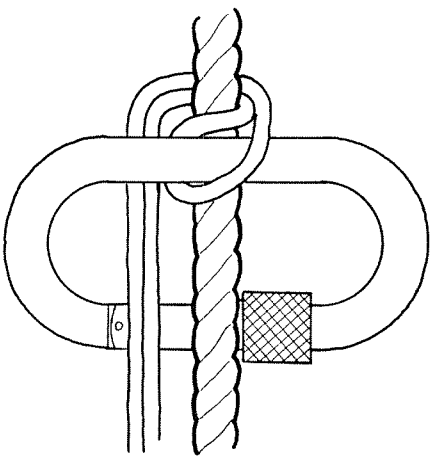


Fig. 31. Single-Wrap Snap-Link Twist.

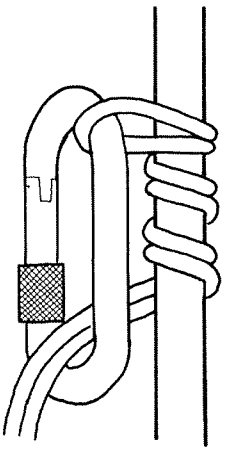


Fig. 32. An unnamed knot that is essentially an inverted rbs knot.

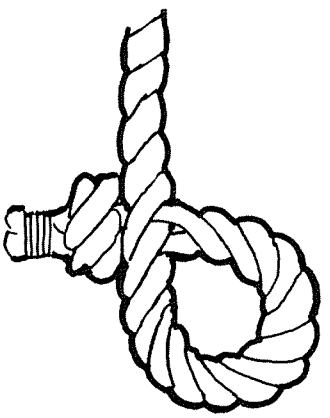


Fig. 33. Unusual Eye Splice.

one-turn carabiner prusik (Figure 24). When I tested the snap-link twist, it did not move as freely as most of the other semi-mechanical knots. Unlike the Bachmann knot, twisting the carabiner did not put any slack into the knot. Pulling up on the carabiner was more safisfactory, but the only method that seemed practical was feeding the sling around the carabiner and standing rope. This was slow for me because I had to work the slack all the way into the knot. A locking carabiner is essential because the sling easily slips over to the gate.

Other Knots. A knot that is essentially an inverted rbs knot has been described by Martin (1968) and Renner (1970) (Figure 32). Its ease of moving is similar to the rbs knot. It is less used than the rbs knot because the rbs knot was invented and described first. The inverted form was invented independently, without any knowledge of the right way to tie an rbs knot.

The semi-mechanical knots described below are of my own invention. They are similar to the Bachmann and rbs knots but are tied with a single strand of rope instead of a doubled sling. To facilitate tying these knots with laid rope, an unusual eye splice was used (Figure 33). The ends are forced through the rope in any of several arrangements, as in starting an ordinary eye splice, but instead of being tucked under the rope strands, the ends are brought together and tied off with any of the several kinds of stopper knots. With braided rope, simply tie a knot in the end and open a hold through the braid below the knot. I

have tried these knots at a practice session, and both work with 1/4" slings. The single strand rbs knot is a little harder to loosen when tied with 3/8" rope.

Finally, it should be pointed out that it is possible to tie a semi-mechanical version of a Spong knot.

MECHANICAL ASCENDERS

Mechanical ascenders, using only metal parts to grip the rope, have become popular in recent years. In comparison to knots, the ascenders have the following features:

They release the rope quickly and thus can be pushed up without any delay for loosening.

Their performance is more uniform over a wide range of conditions. However, if they slip, there is usually no way to increase their holding power.

They do not wear out as fast as knots, but when they do wear out, they are harder to replace.

They are heavier and bulkier, and they must be used with some sort of slings. The combination of slings and ascenders is inevitably heavier than slings that can be used by themselves.

They exert greater force per unit area on the rope because of the smaller area of contact.

They are more expensive (this is the reason given by most non-users for their non-use).

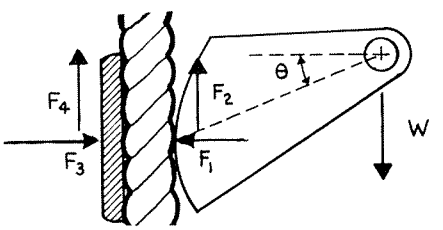
They are difficult to obtain.

Mechanical ascenders can be easily moved up the rope with one hand. It is not necessary to grasp the standing rope under the ascender as it is with knots. The ascenders' advantage is not one of effort. Their lack of friction is balanced by their greater weight. With the best of knots, the rope must be pulled straight for easy loosening. Or the rope must be held for one sharp initial loosening movement. This then is the secret of the mechanical ascenders' speed. They lend themselves to methods where the hands are not moved from the ascender. With systems where the hands are shifted about, mechanical ascenders offer little improvement.

Jumars. The Jumar ascender (Figure 34) is made in Switzerland and is the most popular and, at $32.00 a pair, the most expensive of the mechanical ascenders. It works on ropes of 1/4" to 1/2" diameter, although it is a tight fit on some 1/2" ropes. The safety latch is often filed shorter for use on 1/2" rope so that the cam will open wider. It has an eccentric cam with small conical spikes or teeth that wedge against the rope, and indeed force by the spikes is necessary to grip the rope.* The spiked cam is a subject of controversy, since some claim the spikes damage the rope. In tests, Jumars have been found to cut a rope at 1100 to 1600 pounds of force (Drummond, 1968; Gibbs and Doll, 1969). This is

*The system of forces in the Jumar ascender is:

W = weight of prusiker's body
F_4 = frictional drag on rope
$F_3 = F_1$ = force perpendicular to rope
$W = F_4 + F_2$ if ascender is assumed not to slip
$F_1 = F_2 \cot \theta$
$F_4 = \mu F_3$ (μ = coefficient of friction)



By experiment:
$\mu = .25$, $\theta \simeq 25°$ (on 7/16" nylon rope)
Combining equations:
$W = F_1 (\mu + \tan 25°) = .67F_1$
$F_4 = .37W$; $F_2 = .63W$

The disparity between F_2 and F_4 results from the toothed cams. The teeth must exert a greater drag than friction alone could, since smooth cams would slip.

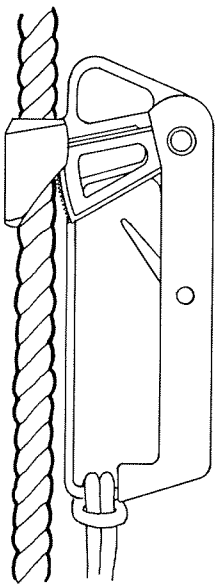


Fig. 34. Jumar Ascender.

much more force than would be applied in normal prusiking.

Jumars have been used for a period of years with only slight, if any, increase in rope wear. On the contrary, the wearing of the spikes by the rope *is* a problem. When the spikes wear, the Jumars will not hold. This could occur in the middle of a long climb, and the slippage at this point might cause rope wear. The life of the cams can be prolonged by loosening the cam with the fingers and holding it open while pushing the Jumar up. I have gotten in the habit of doing this for the lower Jumar since it is often necessary to open the cam on a muddy rope or while near the bottom. The top Jumar receives much more wear. Pushing the cam against the rope while sliding the Jumar up should be avoided. For a long time, replacement cams were not available, but now cams may be purchased from Recreational Equipment Inc. for about $5 with related parts. Since the frames of the Jumar ascenders are aluminum and the cams had a finish that resembled anodizing, the cams were commonly thought to be aluminum. When owners started removing the cams for replacement, it was obvious that the cams were made of a much heavier and harder material, apparently stainless steel. A lot of thought seems to have gone into the cam design. The cam is shaped so that the gripping force varies little with rope size. The toothed surface is curved so that the rope mates into it evenly and the curvature changes along the cam so that the cam radius increases with rope diameter. Jim Johnston and Donal Myrick (1968) give instructions for making replacement cams. They report that their tool steel cams give much longer life than the originals. They apparently made their own cams before replacements were commercially available. I doubt that many people would go to the trouble anymore.

The Jumar units are light (10 oz.), but I find them needlessly bulky. The handles were made large enough so that a person's hands could fit inside them, but I find it more comfortable to grasp the Jumars on the outside of the top half of the frame. The safety latch is an essential feature, because without it, it would be possible to remove the Jumar from the rope just by pushing it upward. In spite of this latch, Jumars can slip from diagonally strung ropes in which the bottom has been tied off so the rope is not vertical, a situation sometimes encountered in mountain climbing. Care should be taken not to loosen the safety catch. I once found myself opening both the cam and the safety latch. The cams can become loaded with mud, presenting a smooth surface to the standing rope, and slip. This can easily happen in a few feet on a muddy rope. Jumars can usually be made to hold by pushing the cams shut. Mud that has collected should be removed between cave trips and not be allowed to harden. Jumars can be snapped on and off the rope very rapidly, which makes them useful for going over breakovers, where they can be snapped off the rope under the breakover and reclipped above it. When doing this, it is necessary to have some way to prevent falling backwards.

There is a common belief that the ropes at one time furnished with the Jumars were cotton (Brison, 1965; Plummer, 1966). This is not so. The best identification I have gotten is "probably linen." If this is true, the strength is about 1200 lbs. Jumars are now being sold with nylon slings and recently perlon slings.

At the 1967 NSS Convention in Alabama, many Jumars slipped during the prusik races, and in one cave everyone with Jumars had trouble ascending, while no one did with knots.

It has been recommended (Deal, 1967; Richards & Hosley, 1965), that a climbing knot be attached to the top hole of a Jumar to guard against slippage, the theory being that if the Jumar slips a couple of inches, the climbing knot will be pulled tight. I consider this practice useless, because a knot cannot be depended upon to grab the standing rope under these conditions. I have rappelled for 50 feet without my prusik safety catching. It may be necessary to set the knot by hand, and even then it may not hold. The same kind of mud conditions that make Jumars slip also make knots slip. If a knot slips, it may be retied so that it will hold, but doing this to a sling attached to a Jumar takes longer than starting from scratch. The Jumar ascenders' advantage of quick attachment is also lost by tying knots for additional security.

It is unwise to depend on Jumars to work at all times, and it is desirable to have some sort of backup system. Some cavers carry an extra set of slings. Others tie the slings running to their Jumars in such a way that they can be removed and used independently.

Roloff Ascender. The Roloff Ascender, also known as the Mother Lode Grotto Ascender (Figure 35), is a copy of the Jumar that costs less than the Jumar and has replaceable cams. The spikes on the Roloff cams are larger and are made of a softer alloy, which wears faster. Unfortunately, there was no attempt to reduce the bulk of the Jumars. They were claimed to be stronger than the Jumar ascenders, although their maker would not make any statement that could be construed as a guarantee. Some independent tests (Anon., 1969) found the castings to break at 710 and 840 lbs, indicating that they are weaker than the Jumars. The placement and size of the holes for attaching carabiners is much more satisfactory than the Jumar. The MLG ascender is no longer available. Much of their construction was done in a home workshop.

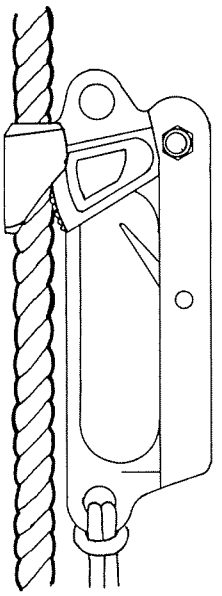


Fig. 35. Roloff Ascender.

Hieblers. The German-made Hiebler rope clamps (Figure 36) work on 1/4" to 7/16" rope although they are a tight fit on 7/16" rope. They can be clipped onto the bight of smaller ropes. Hieblers are smaller than Jumars and weigh less. The most frequent criticism of Hieblers is that the same motion that is used for moving the clamp upward is also used for removing it from the rope, since the two acts differ only by a slight twist. Experienced cavers have found themselves inadvertently removing the Hiebler from the rope while climbing. Even more serious are reports of the Hiebler coming off the rope as weight was being put on it. Consequently, many consider them inherently unsafe. The Hieblers are, however, strong enough. I was able to put 1300 lbs pull on one before it pinched the rope (Thrun, 1968). The tests by Anon., 1970, gave a much different result: the rivet pulled out at 450 lbs. To help guide the rope, latest models have a wire clip that is of some help for safety, but it is too light for the purpose. The Hiebler works by a combination of squeezing and bending the rope. When weight is put on it, the handle swings downward 3 inches, causing some of the climbed distance to be lost.

There has been a report about the sheath of a braided rope becoming worn through and

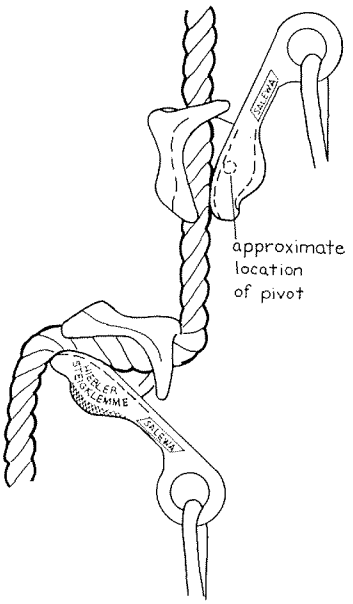


Fig. 36. Hiebler Ascender.

slipping down the core (Drummond, 1968). Hiebler ascenders are about the only thing that will hold after the sheath fails.

Climbing Cams. There are several mechanical ascenders that go under the name of "climbing cams." The main reason they are all included under this heading is that their different originators have applied the same term to them. Most of the later models share a common inspiration, being an improvement on the earlier design.

The first well-publicized design was developed by Henshaw and Morehouse (1965) in Iowa. The originators claim that a lot of thought was given to the shape of the cam in their design. I can see that this would be necessary so that the cam would exert adequate but not excessive pressure on different sizes of rope. Most people who have made their own cams used whatever curve looked right, and didn't do any engineering. Ropes have been damaged by poorly designed cams. The main disadvantage of the climbing cams is that they must be disassembled to be put on the rope which poses the danger of losing parts. Some people have tied cords onto the pieces to prevent this loss.

The Iowa design is similar to the ascenders called "monkeys" that were used in France as early as 1935 (Brison, 1966). The two designs were independent, and their resemblance is just a coincidence. Dwight Deal (1965) made a modified version of the Iowa cam that offered a choice of three pivots for the cam. The design by Lindsley (1966), Figure 37, is a slight refinement of Deal's design. The three holes shown near the nut are for slightly less gripping power, slightly more gripping power, and 3/8" rope. Lindsley gives very precise dimensions and instructions for making the cams, but I am not reprinting them because I think the choice of four pivot holes is indicative of poor engineering. The ideal design would be adequate without adjustment. I am also surprised that Lindsley found a circular arc to be the proper shape for the cam face; the fact that a circle is the easiest curve to lay out may have influenced the pattern. The design of Deal's and Lindsley's cams provides improved efficiency over the Iowa design, but the cams must be pushed up the rope by hand. They cannot be tied to the feet as the original cams were.

Jack Speece (1968) mentions a double-cam design called "bat climbers." He says they work well, but they have no advantage over the single-cam designs. Note the safety catch on the bat climbers (Figure 38). On a two-cam ascender, it is possible to close one cam before the other. The safety catches are

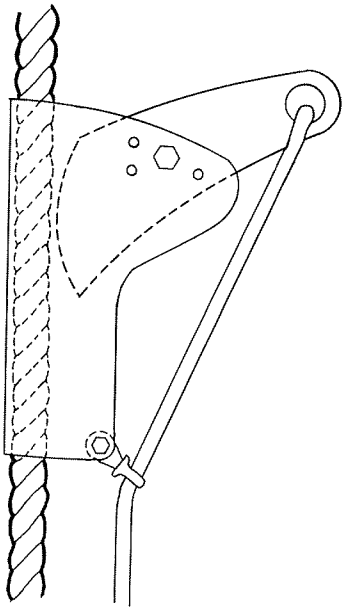


Fig. 37. Lindsley Ascender.

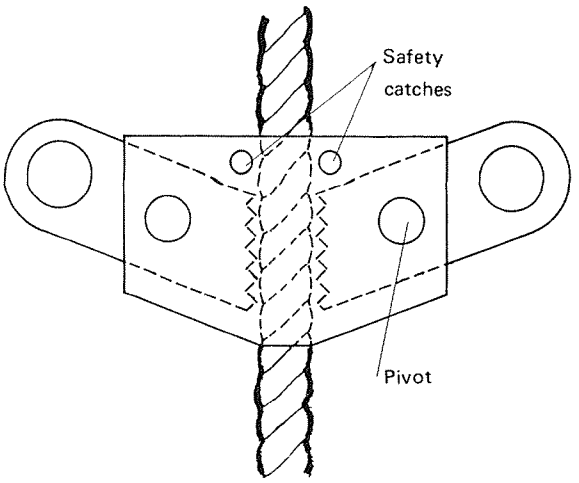


Fig. 38. Bat Climber.

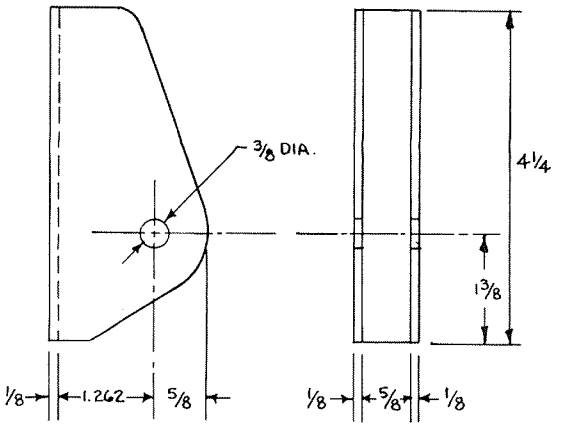


Fig. 40. The body is cut to shape and drilled after it is bent.

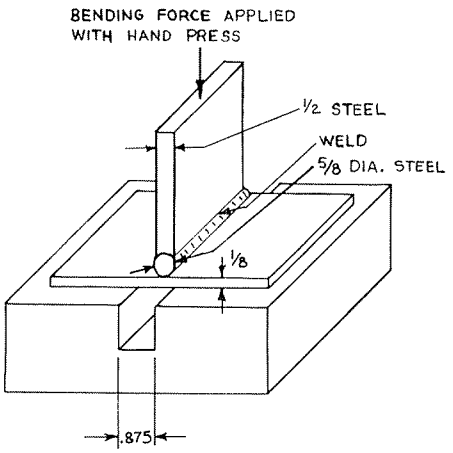


Fig. 39. The body of the Gibbs Ascender is made by bending 1/8" aluminum around a 5/8" rod. Pressing into a groove is a good way to make moderate quantities.

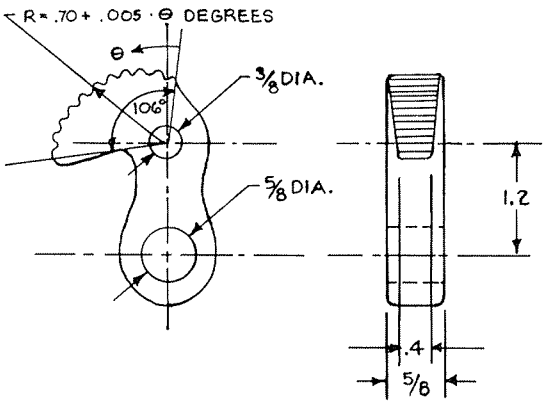


Fig. 41. The cam can be machined or cast from aluminum. Proper dimensions are important. (A more recent design [Gibbs, 1970] uses $R = 0.75 + 0.0075\,\theta$.) Note: Divide surface into 10 symmetrical teeth.

to prevent the cams from swinging far beyond their normal operating position. A similar two-cam design was used by a group from Chicago (Wegstein and Danhof, 1963).

A cam similar to the Iowa design was built by Gibbs and Doll (1969). This design is being sold commercially as of this writing. The plans are reproduced here (Figures 39-42) because the design has been tested to see that it does not damage the rope. The following tests were done by Gibbs and Doll:

One thousand closures of 200 pounds each were made in a one-inch section of both 7/16" Goldline and 1/2" Samson rope. No cut fibers were visible with either rope.

The cam slipped on 7/16" Goldline at 750 pounds. About 10% of the fibers were cut by the slipping cam.

Twenty closures of 1000 pounds each were made on 1/2" Samson. Only slight damage to the outer fibers could be seen. At 1600 pounds the ascender broke the sheath and slipped down the rope.

These results are comparable to some

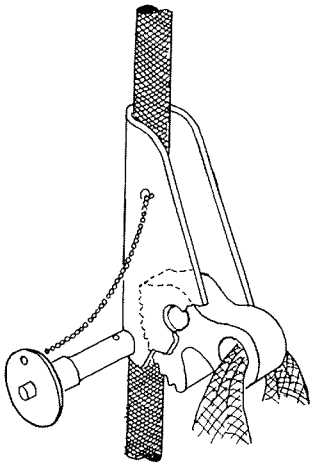


Fig. 42. The finished Gibbs Ascender.

knot tests. Gibbs and Doll concluded that the ascenders were as safe as knots for normal use but not for shock loads.

Another ascender inspired by the Iowa design was built by James Paquette (1969). His design is open on one side. Because the ascender does not have to be taken apart to attach it to the rope, there is no danger of losing parts (Figure 43). To open the cam enough to release the rope it is necessary to swing the block at the bottom out of the way. The block is held in place by a thumbscrew. The body must be made of a strong material. Paquette warns against aluminum and recommends 14 ga. or thicker stainless steel.

French Ascenders. These ascenders are not regularly imported into the United States. They are apparently made for cave use (Figure 44). Their French name translates to "braking blocks." They bear no identifying marks except for "ZEDEL" cast on the surface of the cam. They are available in left and right handed versions, with and without safety catch, a total of four models. The cam action is similar to that of a Jumar ascender. The body is nicely finished. A carabiner must be used for connecting to the ascender as the edges of the holes are too narrow for rope. Each ascender weighs 125 grams. The cam is made of soft aluminum, which may mean rapid wear.

Some tests were run on one ascender. After 600 lbs were put on the ascender, tension was released, and the rope (7/16" Samson) was inspected. There was some fraying on the surface, possibly because the cam still had sharp edges from the casting process. These would get blunted after a short use. Tension was applied again. At 800 lbs the body was bending. At 900 lbs, the body sprang apart enough for the cam to swing through. The ascender was totally inoperable. Even the cam had been bent. These units are

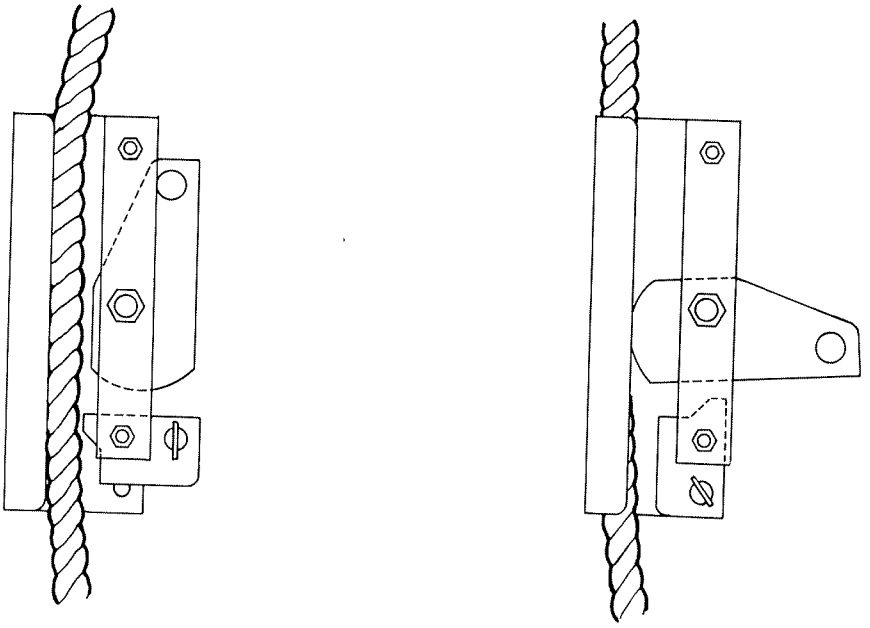


Fig. 43. Paquette Ascender.

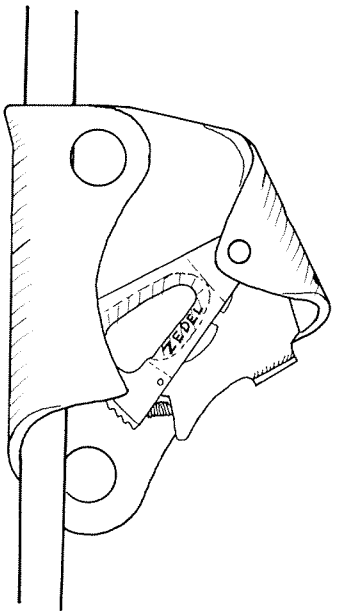


Fig. 44. French Ascender

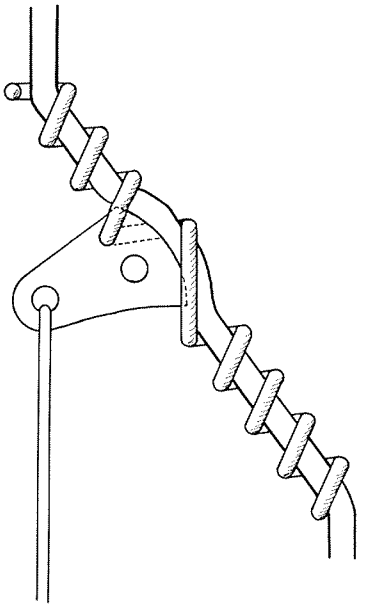


Fig. 45. The Warden Ascender.

weaker than other mechanical ascenders, but are comparable in strength to quarter-inch poly slings, which some cavers use.

Warden Ascender. An interesting ascender was invented and patented (U. S. Pat. No. 3,470,982) by Tom Warden (Figure 45). It consists of a cam and a steel rod that is wound into a spiral shape. The coil has a rectangular cross section in the vicinity of the cam. It can be attached or removed at any point on the rope by winding the rope around it. The second hole in the cam permits the device to be used for rappelling.

Other Mechanical Ascenders. The Klein wire grip, Chicago pattern, is shown in Figure 46. These grips are made for use with electrical wire or steel cable and are very strong, the 1/2" size being rated at 8000 lbs. An improved model with a safety latch to prevent slipping off the wire costs about $15 and would be usable without further modifications. There is a cheaper design with an eccentric cam that is also usable. They are too heavy for caving use, weighing about five pounds each. The large jaws minimize rope crushing. Perhaps some experimenter could make a lightweight version for caving use.

A wide variety of jam cleats are made for yachting use. They have one or two eccentric cams to grip the rope and are very light. Most of them are meant for 3/8" rope, but a few can handle 1/2". The main disadvantage is that the rope can slip out. Some sort of gate would have to be added to make the jam cleat safe for prusiking.

Motorized Ascenders. The possibility of a motorized ascender has long been a topic of speculation among vertical cavers. Motorized winches have been used for a long time, but they are better suited for a highly organized assault than for casual caving. Bill Varnedoe

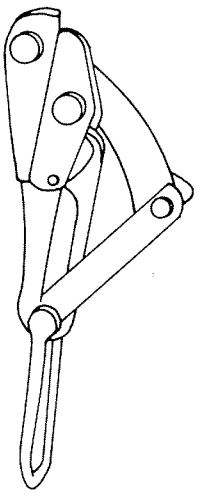


Fig. 46. Klein Wire Grip.

(1967) gave some calculations purporting to show that an electrical ascender is feasible with present motors and batteries. Tom Meador (1968) claimed that he and Dale Lipsett built what is known as the Lipsett ascender. Meador's description was very sketchy. It did not even state what power source was used or how the device was connected to the caver.

The first success with a motorized ascender was by Nevin W. Davis (1969). He showed that Varnedoe was optimistic in several of his assumptions. Varnedoe did not take into account the inefficiencies of the drive train, the fast discharge rate of the battery, or the weight of the machine. Varnedoe also did not take into consideration the situation where a motorized ascender would be used. It would be most useful in extremely deep pits, and, since it is too heavy for one person to carry as part of his personal gear, it would be used by several members of the party. In such situations the high energy density of liquid fuels gives them a great advantage over batteries. With these facts in mind, Davis built MAD--Motorized Ascending Device. The following description was furnished by Davis:

> MAD was developed for those who do not view vertical caving as an end in itself but instead want only to visit the cave at the pit bottom and then exit in the most comfortable manner. Along with the comfort, MAD is a vehicle which could be useful in certain rescue situations.
>
> MAD consists of a one-horsepower, two-cycle gasoline engine with an integral centrifugal clutch and gearbox in conjunction with a home-built transmission which drives a specially designed "Vee" groove pulley. The rope to be climbed is threaded through a rope guide, through a safety device similar to a Jumar ascender, around the "Vee" drive pulley, over an idler pulley, and out of the device (Figure 47). Threading MAD is much like threading a movie projector and like a projector it can be fastened and unfastened at any point along the rope.
>
> A carabiner is clipped to a bar on the underside of MAD and is also clipped to a sling or similar securing device on the operator (Figure 48). The controls are a

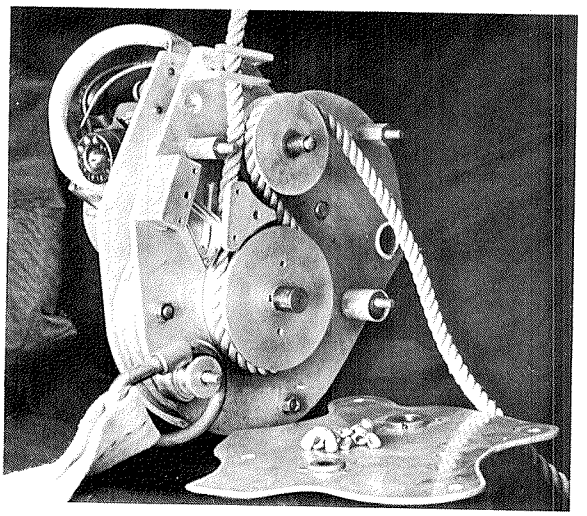


Fig. 47. This view shows MAD with the cover plate removed. It shows the threading of the rope through a guide (top), past a Jumar cam, around the drive pulley, and around an idler pulley. Note the hand throttle and stop button (upper left).

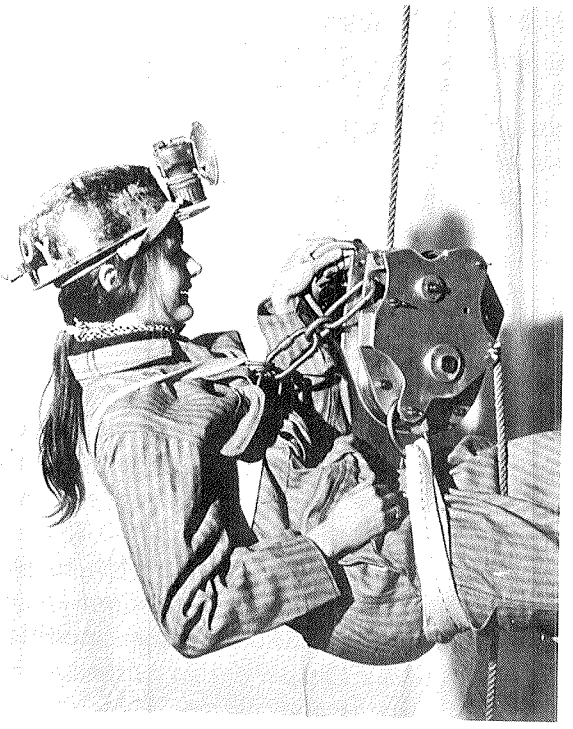


Fig. 48. Use of MAD in ascending. Note that the climber is secured with a seat and an auxiliary sling around the chest to hold her vertical. Both the throttle and stop controls are operated with the left hand.

hand throttle and an instant stop button. When the throttle is turned on, the clutch engages, and the "Vee" drive pulley rolls (climbs) up the rope, carrying the device and the caver with it. The built-in Jumar cam prevents MAD from descending when the clutch is not engaged. In the event of a Jumar cam failure, catastrophic descent can be halted by using the throttle and slipping the clutch. If the engine is not running and the Jumar cam fails (an unlikely event), a terminal downward velocity will be rapidly reached. The velocity will be determined by the amount and viscosity of the lubrication and the total reduction in the gearbox. It is recommended that a set of Jumar ascenders be clipped to the climber in the anticipation of any unexpected failure.

When insufficient rope is hanging below MAD, or when MAD is being started up the rope, a weight of approximately 10 pounds must be suspended from the bottom of the rope so that the "Vee" pulley has sufficient friction to lift the device and the load.

By simply securing the suspension bar on the underside of MAD to a suitable anchor, the device can also be used as a portable winch to lift the rope and/or an injured caver out of a pit. It was used in this way to remove a water soaked rope from Sótano de las Golondrinas.

MAD was designed to climb 7/16" and 1/2" rope and has climbed both Samson 2-in-1 and Plymouth Goldline. To date MAD has climbed over a mile of rope including two trips out of Golondrinas in 25 minutes each (Wefer, 1969) with no failures. The general specifications of MAD are:

Gasoline consumption consumption	- 2 mi/gal (150 lb load at 37 ft/min)
Weight	- 23 lbs Model II (handlebars & twist grip motorcycle throttle) 21.5 lbs Model III (hand throttle)
Load and rate of descent	- 400 lbs max. at 37 ft/min 200 lbs max. at 74 ft/min with a gear change
Materials cost (does not include machining)	- $120

Plans and photographs for building MAD are available for $10 from Nevin Davis, 162 Sycamore Drive, State College, Pennsylvania 16801.

ROPE SELECTION

The selection of a type of rope for making prusik slings presents the caver with a great many choices. When someone finds an especially good rope to use, many others will follow him, mainly because there are too many kinds for anyone to try even a fair sample of them. Each manufacturer makes rope from the most popular fibers as well as some unusual fibers. There are significant differences between brands of rope, since each manufacturer has his own ideas of what rope should be like. I shall try to give some general guidelines and observations on various fibers. The following comments on holding power and ease of loosening apply mainly to the traditional prusik knot. I have observed and used the prusik knot much more than any other.

General Comments. The rope chosen for the standing line will affect the prusik slings that must grip it. Manila rope has a great deal of friction and slippage is generally not a problem with it. A laid nylon line is currently the most popular caving rope. It is slippery when brand new and increases in friction as it is used. Braided nylon, which is becoming popular, is very slippery when new, and its friction increases little with use, causing many a set of otherwise good slings to fail.

The prusik slings are generally of smaller diameter than the standing rope. The greater the size disparity between the slings and the standing line, the better the slings hold. Small diameter slings are harder to loosen, easier to jam.

A hard rope that retains its roundness is desirable for prusik slings. The helical knot, French prusik, and semi-mechanical knots can be used with softer rope. Braided ropes that flatten into webbing under stress are not as good as laid ropes of the same material that retain their shape. A related property that is also important is stiffness. Stiff strands can be pushed into a knot to loosen it. Resiliency, or a tendency to straighten out when the force is removed, would seem to be desirable. No rope I have seen, except metal, has this property. They all acquire set after a short use.

The analysis by Plummer (1963) [Appendix B] gave the result that a slippery sling is needed to grip a slippery rope. This analysis is borne out by experience that slings of synthetic material, which are relatively slippery, hold better on muddy rope.

If the sling rope stretches, its diameter will be reduced. Therefore, when tension is released, the rope will swell up. If this occurs in the knot, it will be hard to loosen. Since the knots and the slings leading from the knots to the caver are usually made from one piece of rope, sling stretch is also an important consideration.

When climbing, the prusik slings are pushed up as far as they will go and the climber's weight is transferred to them. Each time weight is put on a sling, it stretches and some of the distance climbed is lost. The distance lost to stretch is small, but it is repeated at every step of the climb. Imagine a piece of sling material as long as the length of the slings multiplied by the number of steps in the prusik climb. Then imagine the amount of stretch in such a sling when a person's weight is put on it. Vertical cavers notice the stretch in the standing rope because it occurs all at one time. They do not realize that the stretch in the slings can cause more wasted effort than the stretch in the main rope. To minimize the distance lost, the slings should be made of a low-stretch material and be as short as possible.

For a rope to become popular, it must be available locally. An experienced prusiker can make a fair evaluation of a rope's qualities by inspection. If no dealer handles it, the only way to obtain a specific kind of rope is to order a 600-foot spool from the factory. Even if cavers are fairly certain that a rope will work well, they are reluctant to order such a large amount. Again, lack of availability of

5/16" rope is the reason that it is not popular, while 1/4" and 3/8" ropes are widely used.

Manila. Manila rope is inexpensive and widely available. It is made in a great variety of lays, but most dealers have only a single general-purpose grade. The better quality rope is better for prusiks. It takes longer to burn through manila than to melt synthetics with a carbide lamp flame. In one test, it took 1.5 minutes to burn through 3/8" manila, but only 15 seconds for 3/8" polypropylene. Also, if a knot starts to slip, the friction will not melt it. This non-melting characteristic is sometimes cited as a safety advantage. Manila prusik knots can be moved easily, even by those unskilled in loosening knots. The combination of manila standing rope and manila slings is considered one of the best by those who have been prusiking a long time. On laid nylon, 3/8" manila works well when dry, but hardly holds at all on 7/16" braided rope. Manila is affected by water. A wet rope is about 1/10 stronger and has 1-1/2 times as much stretch as a dry rope. The coefficient of friction changes in a complicated manner. Wet knots tend either to jam or to slip. If an attempt is made to wash mud off dirty slings, swelling will occur. The most popular size for manila slings is 3/8". Sometimes 5/16" or 7/16" rope is used, and 1/4" rope is occasionally used for foot slings, where breakage will not be fatal.

Sisal. Sisal rope resembles manila but is somewhat lighter in color. Sisal is 0.8 times as strong as manila. In this country it is considered merely a cheap substitute for manila. Consequently, it is available in only one grade--poor. I was able to buy some good quality, *very* hard lay, 4-strand sisal rope in Guatemala. Unfortunately, it was too stiff, and I could not bend it into tight coils around a rope. It is the only rope I have ever encountered that was too stiff to be used.

Nylon. Nylon is the strongest of fibers, but there seem to be divergent opinions about its holding power. Most people find that it holds well, but some have found it very erratic. It has more stretch than any other rope, and this can cause both a loss of distance gained, as discussed before, and jamming of knots. When the knots jam, they do so suddenly and unexpectedly. (Jamming is less likely on braided standing rope.) Rope of 3/8" diameter is most often used because the stretch in smaller sizes is obvious to most people. Of the synthetics, nylon is one of the most durable.

Polyethylene and Polypropylene. These two chemically similar fibers are so similar physically that they can easily be discussed together. The ropes have a glazed, plastic look. The fibers have a low coefficient of friction, low stretch, and are almost entirely unaffected by water. All the aforementioned properties are desirable. The fibers are soft, however, which increases frictional wear and also leads to a kind of stress fatigue. When the rope is tied around a metal object, the fibers flatten and in doing so lose their strength. These two materials share the lowest melting point of all rope fibers. They can be easily melted through by a lamp flame. Critics of these two materials claim that the rope's tendency to melt if the climbing knots start to slip is a serious safety hazard. The rebuttal is a claim that the knots will *not* slip when tied with polyethylene or polypropylene. Polyethylene is more flexible, and, for this reason, the rope has large fibers. Polypropylene rope has smaller fibers, but not as fine as the fibers in nylon or dacron rope. Polypropylene rope is also limper than polyethylene and is slightly resiliant, whereas polyethylene is not at all resiliant. On a laid nylon rope: 3/8" polyethylene sometimes slips, 1/4" polyethylene always holds, neither jams; 3/8" polypropylene holds even on a very muddy rope; some brands of 1/4" polypropylene jam, wet or dry. On 7/16" braided rope: 1/4" polyethylene may slip on a muddy rope, 3/8" polypropylene barely holds on a dry rope, 1/4" polypropylene will hold on a muddy rope and is easy to move on a dry rope. All the preceding comments apply to the standard 4-coil prusik knot. My personal slings are either 1/4" or 3/8" polypropylene, depending on the standing rope I am using. A

tightly laid rope seems to be best with these materials, apparently because it does not flatten out and is stiffer. A solid braid (like clothesline) that does not flatten out is available and popular in Georgia. Its roundness seems to make it hold better than a laid rope of the same size.

Dacron. Dacron is a polyester fiber. It has low stretch and the highest melting point of any of the synthetics. The rope is soft and limp and does not take a set easily. Because of its softness, prusik knots of dacron rope are hard to loosen. I have, however, heard good reports on rbs knots tied with dacron.

Samson Yacht Braid consists of a braided dacron sheath encasing a braided core. It works well when brand new, but after one use it acquires a set and becomes hard to loosen. It is also expensive.

Mylar. Mylar is also a polyester. This rope is made by an unusual process. Sheets of mylar are cut into ribbons, which are then twisted and stretched into yarns and laid into rope in the normal manner. It has less stretch than any other fiber, with only 1/3 the stretch of the most stretch resistant fiber. The rope is very stiff and difficult to handle because of its springiness, and most knots shake loose almost of their own accord. Mylar holds well and is easy to loosen. Its performance with prusik knots is the best of any rope I have tried, but it will never become popular because of its high price. I paid 26¢ per foot for 1/4" mylar rope.

Wire Rope. Most wire rope is far too stiff to use as prusik slings. The 6 x 42 construction, which is the most flexible available, is still stiffer than any fiber rope and is also weak. Stainless steel cable has a strength of 2000 lbs in the 1/8", 7 x 19 lay, but only 500 lbs in 1/8", 6 x 42 lay.

Linen. I tried a prusik knot with the rope that originally came with Jumars (which I think is linen). It is poor when dry and becomes absolutely useless as prusik material when wet. The wet fibers cling to each other and the rope acquires a dead stiffness like lead wire. (Currently, Jumars are furnished with nylon slings.)

Cotton. Cotton rope is both too weak and too soft to use as prusik-sling material.

Other Fibers. There are some types of rope not available in my home area around Washington, D. C., that are popular elsewhere. Tenstron, made by Puritan Cordage Company, is popular in the southeast. In appearance, it is similar to polyethylene and polypropylene. There is a saying that "Tenstron almost never slips." It is controversial because it is widely used and therefore widely discussed. Actually, Tenstron is about the same as many other brands of polyethylene or polypropylene.

A rope combining polyester and polypropylene yarns is reported to be in use in the Midwest.

PRUSIKING METHODS

General Comments

Up to now I have described climbing knots and devices and have given advice about what rope to use. I have not described how to use the knots. (You can read "mechanical ascender" in place of "knot." Either device can be used in most of the methods described. A few methods are associated with a particular device.) There are many methods of attaching the prusik slings to the body and feet. I will only outline the types of attachment and list the desirable features of each.

The foot attachment normally is just a loop of rope into which a boot or shoe can be slipped. There are two considerations here: comfort and security (i.e., staying on). A single thin rope digs into the feet. To counteract this, webbing or doubled strands of rope are sometimes used, although caving boots are often heavy enough so that no special precautions need to be taken. The slings can be kept from slipping off while prusiking by making the loops a close fit. To hold the feet in the slings if the top sling breaks and the prusiker is left hanging by only the foot slings, additional lashings or a cats-paw hitch may be put around the ankle.

The attachment to the torso is by means of either a chest sling or a seat sling, or both. A chest sling is a loop of rope or webbing around the chest, and when a person hangs in it, his weight is borne by his rib cage. A seat sling places the person's weight on the thighs. It seems unnecessary to emphasize this distinction, but some people have described their prusik system and called their sling by the wrong name. The chest sling is sometimes used with a squatting motion, where the person remains upright and much of the weight is borne by his feet, which are tucked underneath him against his thighs. A person using a seat sling often leans back and lifts his feet in front of him for balance. The two types of sling are not always used as described. Either motion can be used with either sling; but squatting requires less arm effort because the weight is always directly over the feet.

A seat sling is less efficient than a chest sling. When the prusiker sits down in an ordinary seat sling, he lowers his body (or raises his thighs relative to his body) a few inches. When I use a simple seat sling and sit down in it, I lose 15 percent of the distance I have gained by standing up. A chest sling will also move upward on the body as weight is put on it, but this movement is very small.

The main advantage of a seat sling is that is it more comfortable than a chest sling. The seat sling allows a person to stop and rest while prusiking, and on very long drops this is necessary. The weight is borne by a portion of the body that is accustomed to carrying it. Most people do not normally put their weight on their rib cage. In fact, some people have quite sensitive ribs. However, I have heard a claim that it is possible to get used to the weight on a chest sling.

A chest sling restricts blood circulation. I have heard that a person can hang in one for only 5 or 10 minutes before blacking out. Some "safety experts" claim that chest slings are dangerous for this reason, although there would be no danger unless the prusiker were knocked unconscious. A high chest sling restricts blood circulation more than a low one. For some styles of prusiking, a low sling gives as good balance as a high one. I currently run my own chest sling against the lowest fixed ribs. Initial slack in the chest sling will reduce the amount of tension it will have when weight is put on it. A wide chest sling is more comfortable and restricts blood circulation less. Some people use 6-inch wide horse girths for comfort, while others use 1/4" rope for ease of carrying.

There are many hybrid and combination slings in use. Many people use a seat sling as

their main support and have a tie-in to a chest sling. The rope to the chest is seldom pulled taut. Its main purpose is to keep the person from flipping over backwards. I have never found flipping backwards to be a problem, but this depends on a person's build and where he is carrying his pack. Another frequently used rig has the rope from the upper knot running to a chest sling, with a connection from the chest sling to a seat sling that supports some of the weight. In this method, depending on the tightness of the chest sling, the weight distribution can vary from entirely on the chest sling to mostly on the seat sling. Bill Cuddington's rig, which he demonstrated at the '67 NSS Convention, has a seat sling as the main support. A short rope from a chest sling is attached to the rope from the seat sling to the upper knot by means of a prusik knot that could be adjusted to vary the weight distribution. This method affects the efficiency and the distance he leans back. Some people use parachute-harness type slings. These can be sewn from webbing (Olsen, 1961) or made from an actual parachute harness (Varnedoe, 1965; Boyd et al., 1966). They can be both efficient and comfortable. The disadvantages of the parachute harness include weight and bulk.

Gain per cycle is the distance that each knot is moved upward each time a step is taken. This is sometimes referred to as "bite." Perera (1962) claimed that a particular prusiking method was faster because it allowed the largest steps to be taken. This statement needs some qualification. Some time is normally spent in loosening knots, and it is desirable to minimize this time. One way of doing this is to reduce the number of times the knots have to be loosened, that is, to take long steps. There are other factors to be considered that limit the gain per cycle that can be profitably achieved. The leg muscles lose mechanical efficiency as the legs are lifted high, making long steps difficult. If the legs are lifted too high, the prusiker will no longer be balanced above his feet, and more of the work of raising the body will be done with the arms. If a person has very strong arms, he can get a very large bite by leaning far back so that his feet are above his head, pulling himself up with his arms and then standing up in his foot slings. This method works well only for a very few.

Most mechanical ascenders and some knots can be loosened instantly. Even so, it takes time to move the hands from one knot to the other and to grasp the rope under the knot to be moved. Some of the methods developed for mechanical ascenders do not require that the hands be moved back and forth. With loosening time eliminated, shorter steps may be used to advantage. In prusik races, the fastest times using knots are made with large steps. With mechanical ascenders, the fastest times are made with medium-sized steps.

The knots should stay below head level. A person can hold a light object at shoulder level for a long time, and lifting to the top of his head is not too hard, but lifting above head level tires the arms. However, keeping the knots low is not of prime importance. A high chest sling or large bite might justify high knots.

Long-step Methods

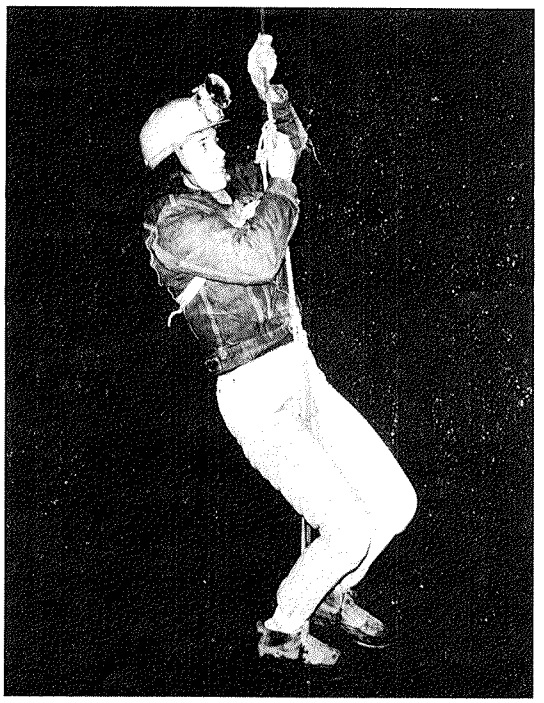
The various prusik systems are described below as a series of separate motions, but in reality the motions are combined and merged so that is is impossible to count the number of individual motions or positions. The way that chest-seat and seat-chest slings grade into each other makes the classification of prusik systems difficult. There are further difficulties: The lengths of the various slings can be altered in such a way that the motions of prusiking are different. Different motions can be used with the same set of slings. In spite of this, because of the need to make comparisons, I shall draw arbitrary dividing lines and number the systems described.

I have heard of five and six knots being used in emergencies where one set of slings was slipping and the person could not or would not remove the old slings before putting others on. A 4-knot prusik, using chest, seat, and foot slings, is possible, but there would be little advantage to it.

(1) Classic Three Knot System. This sys-



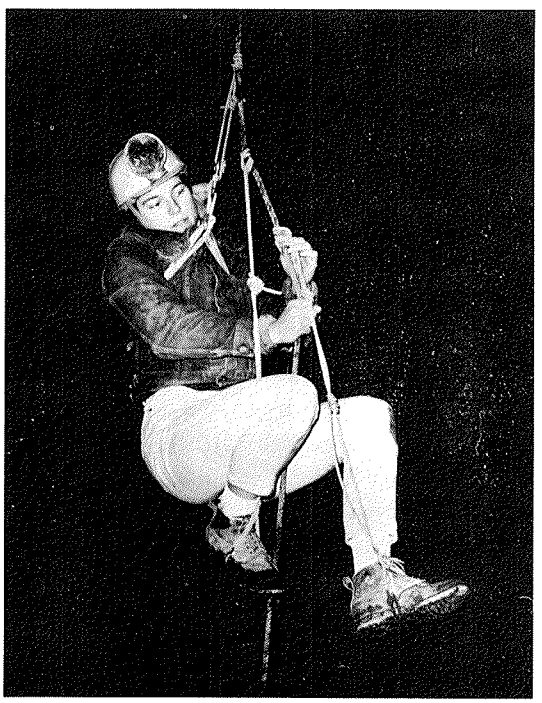
(a)



(b)



(c)



(d)

Fig. 49. The three-knot chest sling prusik. These photographs illustrate the sequence of moves. (a) Start from a squatting position. Most of the weight is on the foot slings. The girl's chest sling, by being taut, holds her upright and keeps her weight centered over her feet. (b) Stand up and move the top knot. The two actions should be nearly simultaneous. One leg is kicked forward for balance. (c) Raise the second knot while standing on the left foot. (d) Squat on the right foot while moving the third knot. Note that both the chest and foot slings are tight.

The girl's slings could be shorter and still work well. Her movements are efficient and graceful. A strong climber can sacrifice comfort in favor of speed and omit the squatting position (a) by simply hanging in his chest sling (Figure 50). A shoulder strap is recommended, especially for men, to keep the chest sling from sliding down.

tem utilizes a chest sling and two foot slings, each with a climbing knot. Plummer (1959a, 1966) has described the normal sequence of moves as follows: Having just finished a cycle of knot moving, the prusiker is in a squatting position with his legs tucked under him. He stands up. At the same time, he slides his left hand up along the standing rope for balance and slides the chest knot up. Then he lifts the next lower knot and right leg. He tucks his right leg under him so that he is sitting on it. This procedure is repeated with the left leg (Figure 49). Once the chest knot is up, the left hand is no longer needed for balance, and it can be used for help in moving the lower two knots. In this system, as in most of the other systems, one hand is used to hold the standing rope below the lowest knot so the knot can be pushed up. The sling lengths for this squatting method are critical. The method for adjustment will be described under System 5.

Contrary to the description just given, many people don't tuck their legs under them for support; they just hang in their chest sling with their legs dangling in front of them (Figure 50). Because they are leaning backwards in this position, they must use their arms to pull themselves upright. The legs can be thrown backward while standing up to help with balance. Either method can be done with the same set of slings. The squatting method is slower because of the extra motions, and results in a shorter gain per cycle. Squatting provides a rest in each cycle, although it is not as comfortable as sitting in a seat sling. The three-knot system is particularly good against a wall. The prusiker can push his chest knot up and hang on it. The legs can be lifted one at a time with no need to use them for balance. Some people use a semi-mechanical knot or mechanical ascender for the chest sling, with prusik knots for the foot slings, minimizing the time that the arms are needed for balance. Certain published drawings of prusiking (Henderson, 1942; Folsom, 1962; Storey, 1965) suggest that there is yet another way to use the classic three knots. After the chest and right foot knots are pushed up, the prusiker stands up on his right foot, then raises the left foot knot. I suspect that these drawings are in error, and were copied, errors and all, by authors that either did not know their subject or were more concerned with getting a book out than with disseminating good technique. The three-knot system is nearly as fast as the similar two-knot Plummer system, System No. 5. The chest knot can be slid up while you are standing up with three knots. With the Plummer system, you must wait until you have stood nearly all the way up. There are two knots to move after standing up in either case. The three-knot system is less tiring on a long climb because you can pace yourself more easily with three knots than with the Plummer system. This system is one of the best for all-round performance. Its one disadvantage is the relative discomfort of a chest sling.



Fig. 50. Three-knot system without squatting.

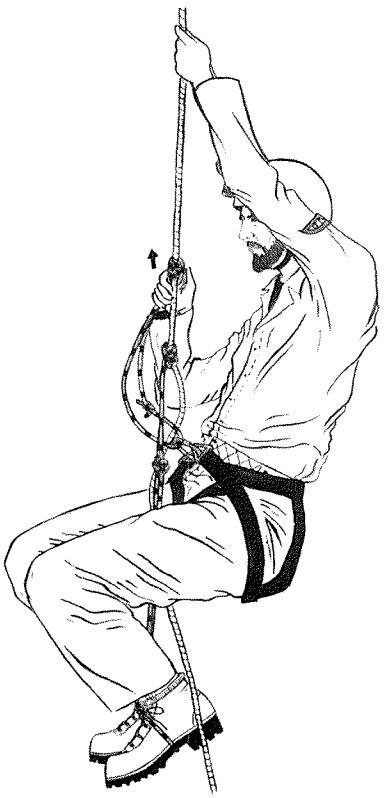
(2) Three-Knot Seat-Sling System. Comfort, due to the use of a seat sling instead of the chest sling, is the main reason for the use of this system. The low support is good against a slope because it permits keeping the body more nearly upright. Against a slope this system may be better than the Texas prusik (System Nos. 3 and 4) because one leg can be used for support and balance while the other is being moved. The three-knot seat-sling system is inefficient due to the use of the seat



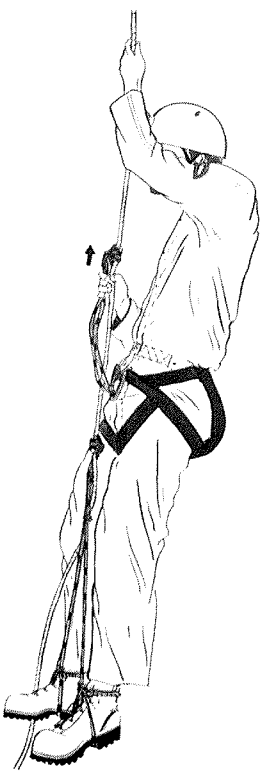
(A)



(B)



(C)



(D)

Fig. 51. The Texas prusik method. A sitting position is the start of the cycle (A). It provides a convenient rest position. The legs are raised and the lower knot is moved up (B). The climber then transfers his weight to his feet and loosens his top knot (C). He stands up and pushes the top knot up (D). He then sits down and starts the cycle over at (A). A very long gain per cycle can be achieved by kicking the leg very high (Figure 52, which shows a one-legged Texas prusik). The high kick can only be used by strong climbers.

sling, and it is slower than other seat-sling systems because of the third knot.

(3) Texas Prusik, first method. This is a seat sling method. The top knot is attached to the seat sling, and the lower knot is connected to both feet by a sling in the form of an inverted "Y" (Figure 51).

(4) Texas Prusik, second method. This method has the top knot connected to a seat sling. The lower knot is connected to only one foot. System 4, the one-legged method, was the original Texas prusik. The two methods are equivalent--the prusiker can kick one foot out of its sling with System 3, or he can step on his sling foot with System 4 as an aid to raising his body. The basic moves are simple: stand up on the foot sling and raise the upper knot (Figure 52), then sit down in the seat sling, pick up the feet, and raise the lower knot. Within rather broad limits, the sling lengths are not critical. The knots should be 20 to 30 inches apart when the top knot is raised, depending on the desired gain per cycle. The knots should be easy to reach at all times. Beginners often make their slings too long. A three-foot long sling looks about right to those who do not know better. This places the knot higher than optimum and causes undue exertion. My personal preference is for very short slings. My top sling is about one foot long after a prusik has been tied with it.

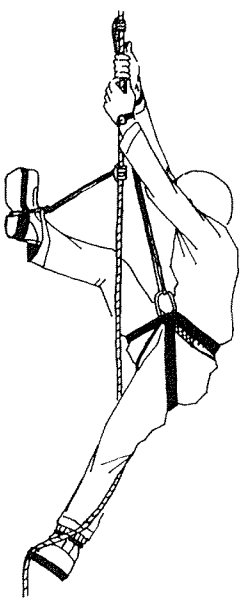


Fig. 52. Texas prusik with high kick.

On a very long climb, people using any method must stop to rest. The seat sling used by the Texas prusik provides a very good method of resting. The inefficiency of the seat sling and the fact that the arms must be used for balance are the main complaints about these methods. Subtle variations in the basic motions can be used. Perera (1962) recommends taking very long bites and leaning far back when the lower knot is moved. This method is slow because much time is wasted in rocking back and forth. For racing, I recommend a different set of motions: with the right arm, hold the top ascender (this can be best done with mechanical ascenders) level with the base of the neck and hold the body rigidly close to the standing rope, with the left hand on the foot ascender. Do knee bends straight up and down, without leaning backward. The hands are not removed from the ascenders. This is very fast because the number of separate motions is smaller than in other methods. For general use (not racing), a slight rocking motion is normal.

System 3 has the advantage that the work is done by both legs. With System 4, lifting is done one-legged. This I have found surprisingly easy--not as hard as one-legged deep-knee bends because the great mechanical advantage of the thighs against the seat sling gets one started moving upward. Once started, it is not difficult to keep moving. I verified this when I tried out an efficient seat sling and found prusiking with it to be very strenuous. To avoid fatigue, the legs can be switched when one is tired, the free leg can be used as a counterbalance when standing up, or the free foot can be placed on top of the other for sharing the load. System 3 works fairly well on a free drop, although it requires some arm effort. Against a vertical wall, where contact is light, it is very good because the wall can be used for balance. On a slope, System 3 is not as good as System 4. With System 3 the legs must be raised and used as balance at the same time. System 4 is excellent for slopes. It is well adapted to Mexican sôtanos, where most of the drops are not free.

The Texas prusik method is good for

caves with several drops because the equipment is light. In addition to a seat sling and carabiner, which are used for rappelling, it requires only two short slings of rope.

(5) Plummer System. This method has been given much publicity by the writings of Bill Plummer (1959b, 1960a, 1961, 1962b, 1962c, 1966). He credits Huntley Ingalls with having invented the method (Plummer, 1960a), although Ingalls (personal communication, June, 1968) does not recall inventing it. However, he was an experimenter and may have tried it and inspired Plummer. At any rate, Plummer deserves credit for refining and publicizing this system.

An arrangement of slings very similar to the Plummer system was shown by Bloxsom and Link (1955) in the first description of prusiking published by and for cavers (Appendix A). However, they used their arrangement as a safety while rappelling and used three knots for climbing.

In the Plummer system the right foot and chest slings are connected to the top knot. (This is assuming that the prusiker kicks right-footed.) The left foot is connected to the bottom knot. There are several ways that the chest and foot slings may be attached to the same knot. Plummer recommends tying a prusik knot around the chest sling with the foot sling. This method has the advantage that the slings can be separated and used with a three-knot system. The sling lengths are critical if the motions described by Plummer are to be used. The position for which the sling lengths are critical is shown in Figures 53 and 54. When the prusiker is hanging in his slings in the squatting-on-heels position shown, his weight should be distributed between his legs and chest, with most of the weight on the legs. The chest sling should be tight enough to hold the body upright. If the chest sling is too short, or the foot sling too long, the back of the heels will not be pulled against the thighs. Either all the body weight will be on the chest sling, or the leg muscles must be used to transfer the weight to the legs. If the chest sling is too long or the foot slings are too short, the prusiker will lean over backwards. He cannot stand straight up from this position without using his arms to pull himself upright. Since he is not directly over his feet, a disproportionate amount of his weight will be on the chest sling. The slings should be long enough so that the prusiker can stand up without bending over. Otherwise, they are usually made as short as possible. Short slings reduce the amount of reaching up that has to

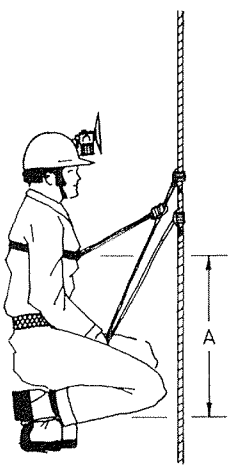


Fig. 53. Plummer Sling Length Determination. Length A.

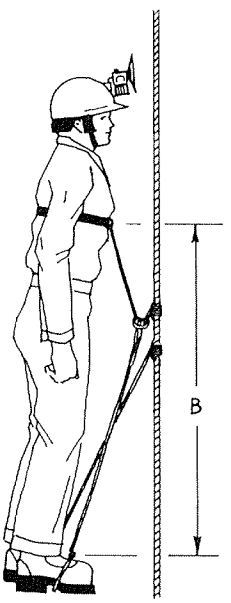


Fig. 54. Plummer Sling Length Determination. Length B.

be done. Plummer (1962b, 1962c) has published elaborate calculations and formulas for obtaining the correct sling lengths. He says (1962b), "First locate a point at the center of your chest, about five inches below your throat, where a rope tied beneath your arms would cross. This is one reference point. The second reference point is the protruding bone on the inner side of one ankle.

"Squat, so that you are sitting on your heels, with knees pointed slightly downward but not touching the floor. Hold your body upright, and lean slightly forward. Measure now between your ankle bone and the reference point on your chest in a vertical line, and call this length 'A' (Figure 53). Stand up, and measure the new distance between the same two points. Call this longer distance 'B'." (Figure 54).

The upper reference point is not necessarily five inches below the throat. It is, more accurately, the point at which the chest harness crosses the chest. I have seen this vary from one to ten inches below a person's throat.

Allowances must be made for the amount of rope used by the prusik knots and some length deducted from the chest sling for the carabiner used to attach it to the chest harness. The lengths finally arrived at are:

	slings of 5/16" rope	slings of 3/8" rope
chest	½(B-A) + 4½"	½(B-A) + 7½"
right leg	½(A+B) + 18"	½(A+B) + 20"
left leg	½(A+B) + 16"	½(A+B) + 18"

These lengths are for the overall length of the finished slings. They are different from the lengths given by Plummer because the lengths given here are for foot slings after a foot loop has been tied in them. The chest sling may be shortened by half the distance that the chest sling is able to move up and down, or this slack can be handled by sliding the foot sling down on the chest sling. When you try out these slings, you may find that the position you assume while hanging on a rope is not quite the same as you had when squatting on a floor. You may want to change the sling lengths slightly, or the adjustment of the right foot sling might be sufficient. Plummer gives formulas for the cut lengths of rope that are to be used for making the slings. If you fashion your slings in the same design, use the same knots, make your splices the same way and wear approximately the same size shoe as Plummer, you might find it useful to refer to his formulas. The lengths given are not the only ones that will work. The chest sling alone can be lengthened, or both the chest sling and right foot sling can be lengthened. The left foot sling can be lengthened a couple of inches (some people like to have their foot slings the same length so that they will be interchangeable) or shortened until the knot can barely be reached. The same slings will work for a three-knot system, although they will be two or three inches longer than necessary. If the formulas for sling lengths seem confusing or unnecessarily complicated, or if they don't work for you, fall back on the criteria that the formulas were derived from. The slings can be easily shortened or lengthened, provided you did not follow Plummer's advice to splice the slings together. I would suggest obtaining nearly correct lengths by squatting on a floor and then making the adjustments while hanging on a rope. Of course, if you are one who does not go through a squatting position and simply hangs in his chest sling, the



Fig. 55. Wrong position to obtain Length A.

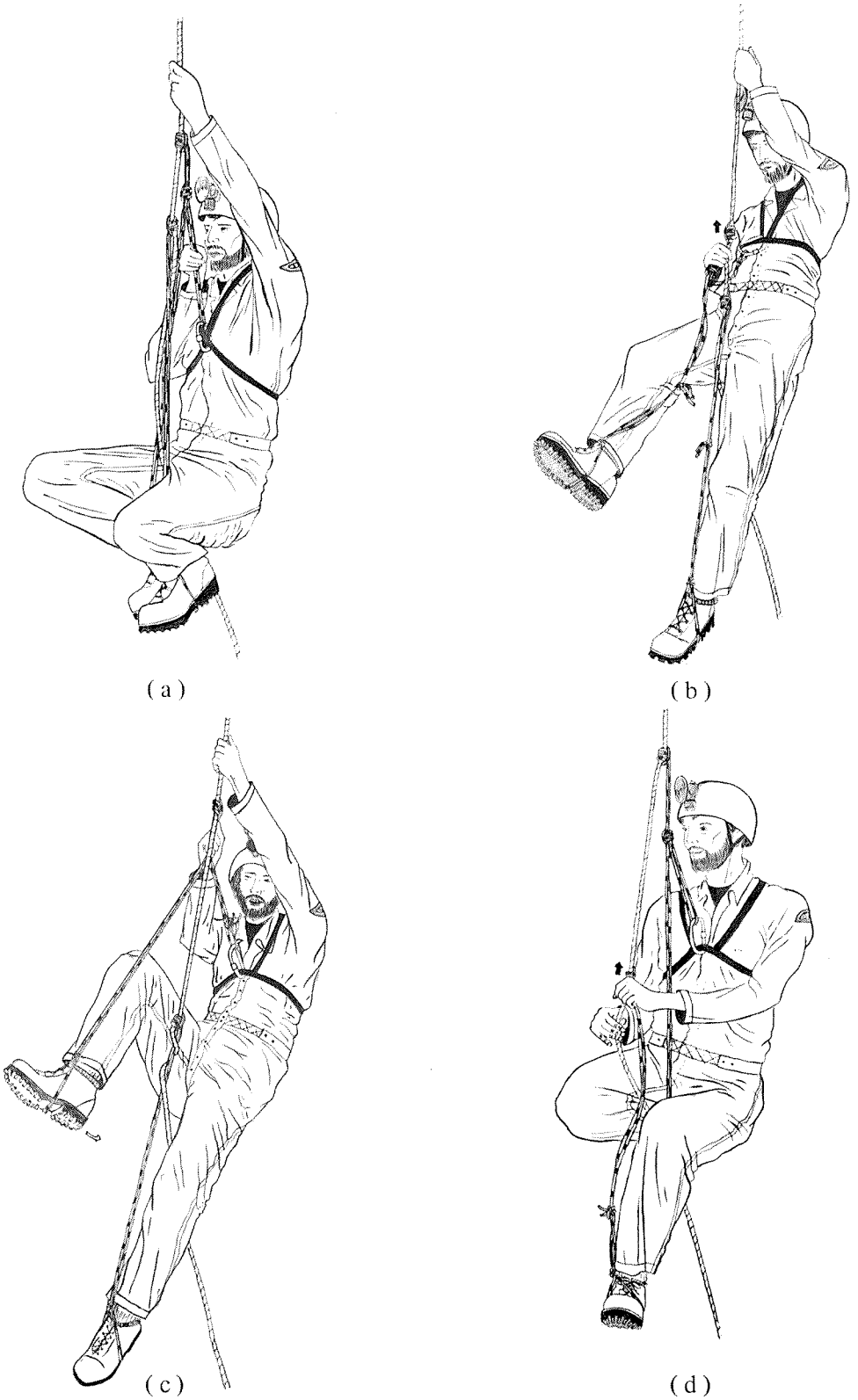


Fig. 56. The Plummer System. (a) Start from a squatting position. (b) Stand up. When you are nearly erect, kick your right leg forward and loosen the top knot. The left arm does very little work in maintaining balance when the leg is kicked forward. (c) When the top knot is all the way up, tuck your right leg under you. (d) Squat on your right leg while you move the lower knot. Most of the weight should be on the foot with the chest sling just tight enough to hold you erect. The motions should flow smoothly into each other throughout the cycle.

lengths are not as critical. Apparently some people (Storey, 1965), including myself at first, thought that squatting on one's heels meant attaining the position in Figure 55 with the weight on the heels.

I shall describe the motions used, according to Plummer (Figure 56), with my comments in parentheses: Starting from the squatting position, stand straight up. Slide your right hand along the standing rope for balance as you stand up. (Either hand can be used. It helps to be able to switch arms when one gets tired.) When you have risen most of the way, kick your right foot up and forward to help you lean close to the standing rope. When you are all the way up, grasp the standing rope as high as you can reach to help you keep your balance. (If you are very careful and have no pack on your back, the arms are not needed at all for balance.) Grasping the rope high with the elbow straight is less tiring than pulling yourself in with the elbow bent. (It is difficult to get a grip on a muddy rope.) As soon as possible, while you are still moving upward, move the top knot up with your left hand. When the sling is tight, tuck your right leg under yourself and sit on your heel. You can now use both hands to move the lower knot connected to your left foot. Tuck this foot under yourself, so that you are back in the starting position. The movements should merge into each other. There should be no pause in any of the positions. (Sometimes you have to pause, especially if the knots are hard to move.)

I have found that when I am trying to race, the motions of kicking a leg up and tucking it under are both time-consuming and tiring. I use the squatting position mainly for resting and moving slowly. Your technique will depend partly on how well you can hang in your chest sling.

The Plummer method is not entirely satisfactory against a wall. You must move your right foot up and hold yourself away from the wall with it at the same time. Plummer recommends changing to three knots for prusiking against a wall, but the three-knot system might be used for the entire climb to save time. Removing the right foot from its sling is a less satisfactory technique, but it helps. This practice is not as good as System 4 because the chest sling pulls you closer to the slope.

Because of its lack of a rest position, the Plummer method is not popular for long drops. It appears to be best suited for fairly free drops of under 200 feet.

Short-Step Methods

The five methods discussed so far have been long-step methods, all of which require a deep knee bend or squatting motion. They were all developed with knots and have been used under all caving conditions. More recently some short-step methods have been developed using mechanical ascenders. Although long-step and short-step methods tend to be best suited to different prusiking systems, almost any system can be used with either long or short steps. The long-step methods are inherently inefficient. This is evident from the relatively low speeds attained. Ten feet per minute is average; twenty is very good on a sustained climb. It is possible to put out the energy for a climb much more rapidly. I can easily climb 500 feet of stairs in 10 minutes. After climbing the stairs, I was less tired than after a long prusik climb. The greater exertion of the long-step prusik methods is due to the lesser mechanical efficiency of the deep-knee bend. The lower speed of the long-step prusik methods has several causes. With knots it is necessary to move the hands from one knot to another and to the rope. As explained before, the arms are generally used for balance and for grasping the rope below the knots. These movements take time. I would estimate that when prusiking I spend half the time shifting my hands around. Even when the hands can be left on the knots or ascenders, the long-step methods are at a disadvantage. The climb has two distinct movements--stand up; raise legs. With the best of the short-step methods, the Mitchell method and the Ropewalker, every move results in an upward climb.

The short-step methods are newer and have not been tested as much as the long-step methods. They work best when a single fast

climb can be made. They have not been tested under as many combinations of slope, mud, and breakovers as the older methods. The systems where ascenders are tied to the feet are especially vulnerable to jamming. This is not a blanket condemnation, merely a warning that problems may be encountered with these methods. Some thought should be given to emergencies. The novice is often tempted to use a system merely because of performance in races or on the basis of well-publicized claims. Nearly every new device or technique has been claimed to be vastly superior to all other methods in its introductory article.

(6) Jumar System. This method is described by the circular that comes with each pair of Jumars (Brison, 1965a). A chest sling with a carabiner attached to it is worn. A sling rope passes from each Jumar to a foot, with both slings running through the carabiner or under the chest sling. Figure 57 is traced from the Jumar circular.

The foot connected to the upper Jumar is the lead foot. To climb, raise your lead foot and stand up (one-legged) on it. Lift your trailing foot and move the lower Jumar up. The chest sling is used only for balance, and no weight is put on it. Most people use a high, tight chest sling to keep them perfectly vertical. The arms are not needed for balance. They are held high, which is tiring. The lead foot also gets tired from doing all the lifting. You can switch legs very quickly by unclipping the lower Jumar and clipping it on above the other one. A squatting motion that uses both legs at the same time should be possible, but I have never heard anyone recommend it. Small steps require less effort than long ones. The method is fast and works well on free drops. Against a slope you can lean back and use a natural walking motion. If the slope is far from vertical, however, you are pulled forward into an awkward position. The Jumar system excels on tight drops. Some drops are narrow enough so that you can't swing your legs and use your arms freely, and are too slick for chimneying. In these the Jumar system with small steps is the answer.

The lack of a good rest position is one of the frequently cited disadvantages of the Jumar system, although there are several ways of resting with the Jumar method. Most people do not find stopping and keeping their knees straight to be relaxing. If you just stand in your slings with knees bent, your knees may be pushed against your shoulders, a position that is neither comfortable nor easy to get out of. Some sit cross-legged on their foot slings. A carabiner can be attached to the chest sling and clipped onto one of the Jumars whenever a rest is needed, or it can be left attached to the lower Jumar while climbing. Many find a chest sling uncomfortable for resting, as explained before, and have a connection between one of their Jumars and a seat sling. This is the most popular method of resting while using the Jumar method. It also serves as a safety device. There is no direct attachment between your body and the ascenders in the basic Jumar system. If your feet slip out of your slings, you fall. A connection between one of the Jumars and a seat or chest sling will prevent this. Various methods of tying the sling ropes to the feet can also be used for safety.

(7) Cams on Feet. This method was described by the originators of the climbing cams (Henshaw and Morehouse, 1965). As I have seen this method, it uses a conventional seat sling with top cam tied to the seat sling

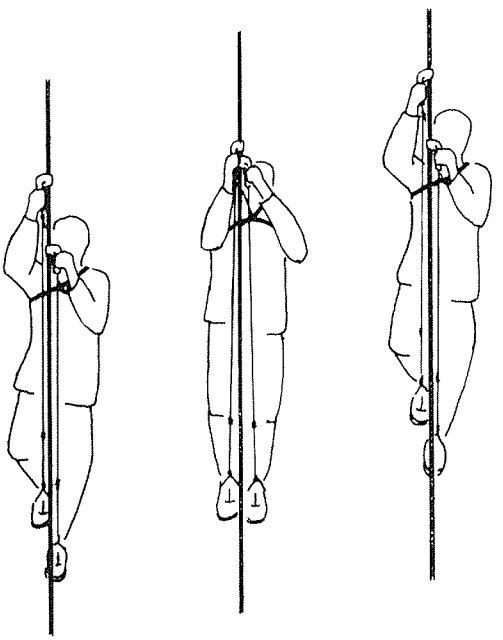


Fig. 57. The Jumar System.

by a short rope. The cams are attached to the feet with very short slings. The feet are moved up the standing rope alternately, as in climbing a ladder, with the hands used to grab the standing rope and hold the body upright. The top cam is just pulled along and only used for resting. To use this method you must either lift yourself one-legged or hold yourself on one leg. Because of the loose attachment of the cams (if you follow the suggestions of the originators of this method), the squatting on heels position of the Plummer method cannot be used unless you sacrifice efficiency or use your hands to move the cams up. There are other motions possible with the cams rigged the same way. You can lock the top cam by hand and use the motions of the classic three-knot prusik, or you can hang on the top cam and bring both feet up together as in System 4. I have also seen a style equivalent to a Texas prusik used with the cams on the feet. The top cam was moved up and weight put on it with each step. The only unusual thing was the cam was tied close to the feet. Tying a mechanical ascender to the feet has two disadvantages. There must be tension on the rope below, so that the person using cams tied to his feet cannot be the last one up. Because of the slack in the foot slings, the feet must be raised higher than the cams. The attachment should be tighter for greater efficiency.

(8) Inchworm Method. This method is known by several different names. "Inchworm" seems most popular, and "Pogo stick" is also a frequently used name. It was first presented at the 1966 NSS Convention by Charles Townsend, who called it the "armless, double-foot and seat-chest sling ascending method" (Townsend, 1966). This cumbersome name probably has not been used by anyone else since then. (Townsend presented another idea in his paper that has not caught on--a method of epoxy-cementing nylon webbing to Jumars.) Mechanical ascenders must be used with the inchworm method. The feet rest on a crossbar that is clamped to an ascender between the feet, and some sort of lashings are used to keep the ascender attached to the feet. The upper ascender is tied between a seat sling and a chest sling. The motions are simple and require no skill, as they merely involve standing up and sitting down (Figure 58). When you stand up, the top ascender is pulled up by the chest sling. When you sit down, you transfer your weight to your seat sling and lift up your legs, lifting the ascenders with them. You can do this without using your arms at all, but it helps to reduce friction if you pull yourself close to the rope. In the prusik races at the 1967 convention, a young boy completed the race in a very fast time using the inchworm method, prompting others to start tying Jumars to their feet and rigging various types of body harnesses. All the racing times using the inchworm method were relatively fast. Apparently a skilled person using other methods can go faster, but the inchworm method is a great equalizer for the less skilled. Some unusual advantages are claimed for the inchworm method. Townsend has climbed out of a pit using only the foot ascender and then using only the chest ascender, proving that it still is possible to get out of a pit if one ascender fails. A simpler way, I think, and less tiring on the arms, is to carry an extra sling. A photographer, coming out of Golondrinas in Mexico, using the inchworm method, was able to adjust his camera without having to stop.

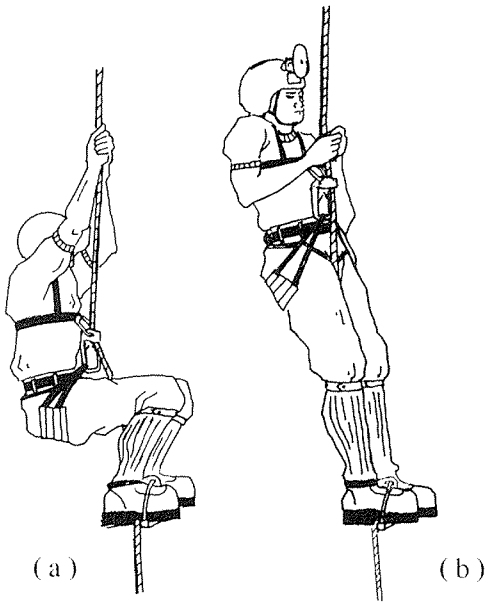


Fig. 58. The movements in the inchworm method are simple: (a) sit down; (b) stand up. The arms are used for balance.

A single breakover is easily negotiated, because both arms are free and can be used to push away from the edge. A wall gives much more difficulty because the feet are together, and the upper ascender pulls the body toward the rock face. Because there must be tension on the rope beneath the climber, the person using the inchworm method usually cannot be the last one up, although the rope can be weighted by tying it to a pack or other object. Under severe mud conditions it is often necessary to lock the Jumar cam by hand. It is difficult to lock the lower cam with this method. The inchworm method is not a general-purpose method and can be used to advantage only under favorable conditions, i.e., on a clean, free drop.

(9) Mitchell Method. This is a modification of the Jumar system. There had been attempts to distribute the climbing effort between both legs by shortening one of the foot slings. The early attempts gave about the same result as System 11--the method was fast, but too much arm effort was needed to hold oneself close to the rope. To counteract the tendency to lean back, Dick Mitchell ran the standing rope under his chest harness. He used this method to win the prusik race at the 1967 NSS Convention, and it has been used to break records since then.

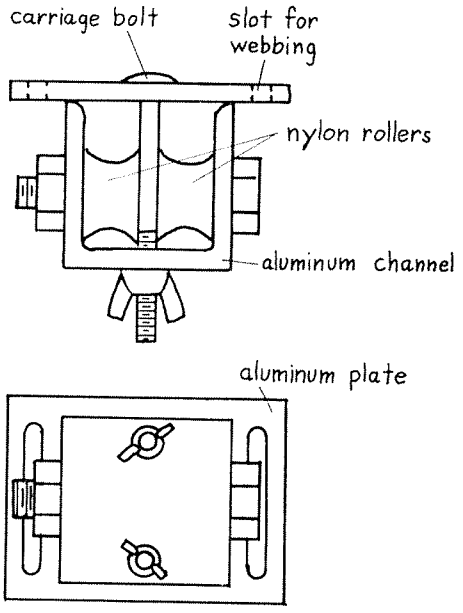


Fig. 59. A simple design for an ascender box. The dimensions and materials are not critical.

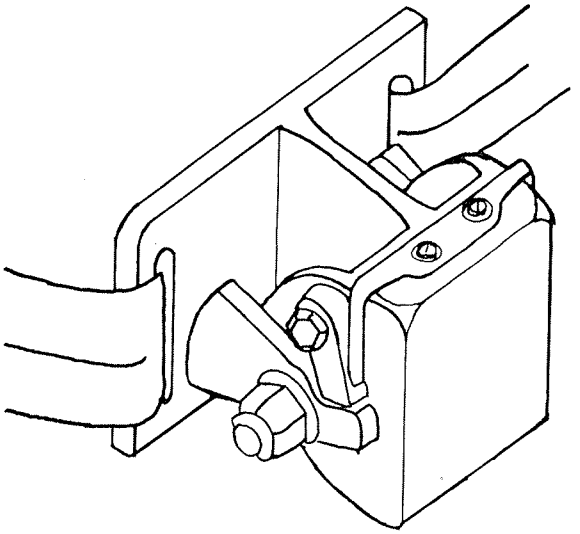


Fig. 60. An advanced ascender box. Ropes may be inserted and removed very quickly.

A high, tight chest harness is necessary. Mitchell (1967) recommends a wide, strong harness of his own design. (I will not describe it here, as I have observed that nearly everyone ignores descriptions of chest harnesses and designs his own.) The standing rope and the lead foot sling are run under this chest harness. There is probably no reduction in friction if the rope and sling are run through a carabiner rather than against the webbing of the harness. The coefficient of friction of nylon rope against aluminum is .25; against nylon webbing it is .32 by my experiment. With a carabiner, the prusiker leans back further and pulls harder against the standing rope, resulting in no decrease of friction. The use of a metal frame fitted with pulley wheels greatly improves the efficiency of the Mitchell method by reducing friction. Some sort of rigid box is necessary. Two "rescue pulleys" will bind and not reduce friction. Two designs are shown. Figure 59 is perhaps the easiest to manufacture of any design. The box was drawn to scale, but the dimensions are not critical as long as the rope will fit through it. The second design, Figure 60, is very sophisticated. It features swinging gates to hold the rope in place with spring loaded safety catch-

es. By using a third Jumar on a seat sling, clipping it onto either the slings or standing rope, and releasing one or both ropes from the ascender box, a great many prusik methods may be used. This versatility is useful against walls and at ledges. An ascender box can also be used with the ropewalker method to eliminate all use of the arms. The ascender box is both bulky and heavy. The individual must decide to use it or not according to the amount of time and money he wants to invest and the amount of weight he wants to carry. It seems primarily a tool for the deep pit specialist.

The sling to the upper ascender should be as short as it can be and still keep the ascender above the chest harness while the prusiker is standing upright. The lower ascender should be as low as can comfortably be reached, to allow the longest steps possible with the Mitchell method. If these long steps are too tiring, smaller ones can be taken. It may be advantageous to make the sling lengths slightly shorter than ideal when standing on the ground, because when you are on the rope, your legs will be pulled slightly forward and up.

The climbing motions are simple and obvious once you have rigged in (Figure 61). Just put your weight on one leg and raise the other leg and ascender, then do the same with your other leg. The motions nearly duplicate the motions of ladder climbing. Do not try to raise your upper ascender as far as you can reach. This will result in too large a step for the lead leg and will soon tire that leg. The steps taken by each leg should be about the same. The actual size of the steps taken depends on individual strength and preference. A gain per cycle of 18 inches is common, but longer gains up to 3 feet are used. The arms are not used for balancing at any time.

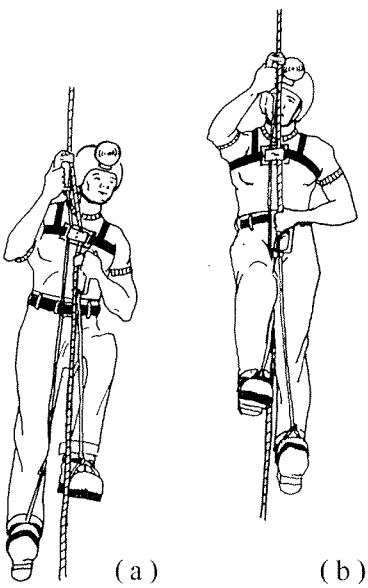


Fig. 61. The Mitchell Method: (a) stand up on the left foot while raising the top ascender; (b) stand up on the right foot while raising the other foot and ascender. These drawings show an ascender box being used.

If there is tension on the rope, the hands will be needed only for pushing the ascenders upward, so that one hand can be kept on each ascender. The Mitchell method is very poor against a wall. This is unfortunate in view of its excellent free-drop performance.

A seat sling can be connected to the lead foot sling for resting purposes. This acts also as a safety device, because the Mitchell method, like the Jumar system, has no direct connection between the standing rope and the climber's body.

The Mitchell method is less tiring than many others. While racing, I have found that the systems using a deep-knee-bend motion (Systems 1, 3, 4, and 5) tire the muscles just above my knees. The Mitchell method is faster and less tiring for me because the work is done by the larger muscles at the back of the thighs.

The Mitchell method depends very much on the smooth functioning of mechanical ascenders. I tried this method with knots that were a bit difficult to move, and it became most strenuous.

(10) Ropewalker. The ropewalker is the newest of the short-step methods (Gibbs and Doll, 1969). It uses mechanical ascenders tied to the feet as in System 7, but one ascender is located at knee level so that the effect is similar to that of the Mitchell method, in that the weight is alternately lifted by each leg. Although one ascender is attached near the knee, as shown in Figure 62, the weight is supported by the foot. The only purpose of the knee band is to raise the ascender when

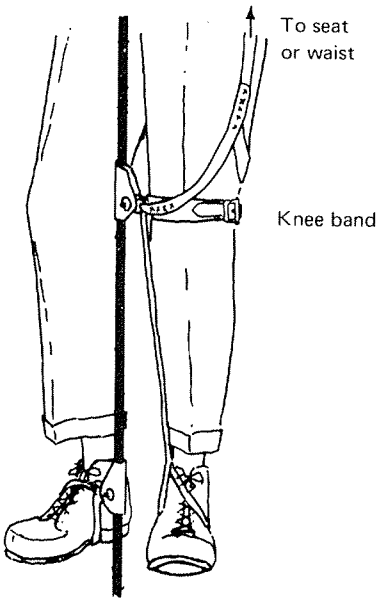


Fig. 62. The Ropewalker. The body weight is transferred to the cam ascenders with endless nylon loops from the instep of each foot. An elastic strap and nylon safety sling support the upper cam ascender against the knee. From Gibbs and Doll (1969).

the leg is lifted. For greatest efficiency the knee ascender should be tied as close to the knee as possible. Positioning it further up the thigh reduces the amount of lift provided by that leg. The sling attaching the ascender to the other foot should be kept short. The two ascenders on the legs are used with an additional ascender or knot attached to a chest or seat sling. The top knot is a safety against falling backwards, and is used for resting. The connection between the seat sling and the knee ascender is an additional safety factor. It also keeps the knee band from sliding down. While climbing, the arms are used for balance, and the top knot is not tightened. The ropewalker system is strenuous for the arms. The best way to keep the arms from tiring is to climb fast, since arm exertion is proportional to the time spent climbing and the leg exertion is dependant on the distance climbed. The originators of the method recommend climbing in bursts of about 40 feet followed by rest stops. If one of the foot ascenders should fail, lifting can be done by both feet, as in the Texas prusik, by re-rigging the foot slings or by stepping on one foot with the other.

There is generally some difficulty in getting started. The easiest way is to have someone hold the rope below the climber although the rope can be shaken through the climbing cams, especially if they are a loose fit for the rope being used. It is almost a necessity to have someone hold the rope, although it may be possible to get started by tying a pack at the bottom. The effectiveness of the system depends on the smooth working of the ascenders since they are effectively out of reach. To lock the cams, the legs can be swung sideways. Jumar ascenders can also be used, but it is harder to shake the rope through them at the start of the climb. With most other climbing systems, the knots or ascenders can be worked by hand to loosen or lock them. The ropewalker, at the time of this writing, has achieved the fastest times in prusik races, although from a theoretical standpoint, it is difficult to see where it has any advantage over the Mitchell method.

Other Systems

The systems following are essentially long-step methods that are not as well tested as other long-step systems. They have few users. They vary in potential and are placed in a miscellaneous category because they do not fit easily into either of the previous categories.

(11) Spiderweb System. One of the difficulties with the Plummer system is the amount of weight that is put on the chest sling. The proponents of the Plummer system claim that most of the weight is supported by the feet. However, some weight is put on the chest sling, and this stress is increased by such common difficulties as being too tired to kick high, or being off balance from carrying a pack. Even if these difficulties are argued away as poor technique, the fact remains that many cavers complain of them. To retain the efficiency of the Plummer system while removing some of the weight from the chest sling, an additional connection can be rigged from the upper knot to a seat sling. This connection can be made from the seat sling to the chest sling if the two slings do not tend to

move relative to one another during the ascending motions. One of my rigs, which was truly worthy of the name "spiderweb system," had the chest sling, seat sling, and right foot connected directly to the top knot and the seat sling and left foot connected to the lower knot. The motions and adjustments were about the same as described for the Plummer method, with the additional requirement that the connections to both seat and chest slings be tight when the upper knot was raised. This system was both comfortable and efficient and had the desirable feature of redundancy. I could remove any of the climbing knots from the rope (the rig was convertible to a three-knot system) and hang from the others with no danger of falling backwards. If anything but the climbing rope broke, I would be safe. I abandoned this system because it took too much time to tie and adjust. The lengths were hyper-critical–a half-inch difference from the optimum length was bothersome.

Another system that distributes the weight in the same manner and is easier to adjust was described by Mike Kaczmarek (1967) and developed independently by at least one other caver. This system is shown in Figure 63. Kaczmarek used adjustable foot slings, which are omitted for simplicity in the drawing.

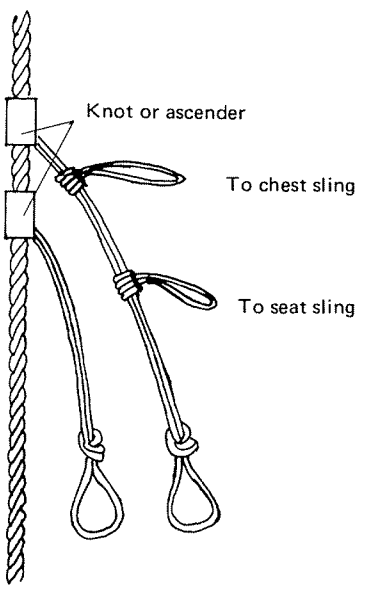


Fig. 63. Kaczmarek System.

The principles involved in obtaining sling lengths are about the same as those described for the Plummer system. I recommend becoming familiar with the adjustments of the Plummer system before trying this one. The slings can be shortened and lengthened in many ways, provided the lengths of the other slings or the adjustment of the prusik knots are changed to compensate. With the top knot raised, the prusiker should be squatting on one foot, and the connections to seat and chest should be tight.

(12) This system is another variation on the Plummer system. The right foot sling and a seat sling, rather than a chest sling, are connected to the top knot. The left foot is connected to the lower knot. A squatting motion can be used, but the balance is very delicate because the seat sling attachment point is low in relation to the prusiker's center of gravity. The squatting motion is efficient because the leg provides support when it is being sat upon. Leaning back is natural and provides a rest position, but it sacrifices efficiency. The people who use this method have found it to be steady and comfortable, but slightly slower than the other methods.

(13) In this system the upper knot is about at chest level when you are standing on a floor. The right foot and chest sling are connected to it. The lower knot is at waist level and is connected to the left foot and seat sling. This was an attempt of mine to duplicate the motions used in ladder climbing. I would raise my right foot two feet and then raise myself on it; then I slide my lower knot a distance of four feet and raise my right foot two feet again. This method was very fast in practice sessions, but in caves it was very tiring. One-legged lifting could be done only when I was fresh. Shortening the bite did not help much. I continually had to pull myself toward the rope with my arms. This method was fast for short climbs but too tiring for a long climb.

(14) Wisconsin System. This ingenious rigging system was developed by a group at the University of Wisconsin (Boyd, Foster, and Olmstead, 1966). They have described

and evaluated it in great detail, and I will quote their report at length, because I have not given the system a good test. They use Jumars and a modified parachute harness, although a normal seat and chest sling could be used just as easily, perhaps with a loss of efficiency. Slings run to each foot from the lead Jumar through a chest carabiner similar to that used in System 6. The lower Jumar is attached to a seat sling by a very short sling. This method is very unusual in that the feet are connected to the upper ascender while the body is connected to the lower one (Figure 64). The Wisconsin report says:

> Clip on the lead Jumar and drop the foot-loops through the chest carabiner. With foot-loops on, sit in the rig and raise the lead Jumar as far as you can, lifting both feet together directly under you. Now stand up, raising the lower Jumar as you do. That's all there is to it.
>
> Now a bunch of "warnings." (a) Make sure the foot slings are on the outside of the main rope. (b) The main rope can be run through the carabiner along with the foot slings or be kept outside it. We've found the latter to be preferable. (c) As you stand up, the foot slings draw down through the carabiner, pulling you into the rope. Later on, if you note extensive abrasion caused by the carabiner on the foot-slings, it means you're leaning back too far in the harness. If so, shorten the rigging on the lower Jumar. (d) Your right arm should not be overtaxed despite the fact it is constantly raised above your head. If it is, it indicates you're leaning back too far in the harness or your "ascending motion" is poor. Your feet should be raised under you to produce the position of a deep knee bend. With some practice, a "rocking motion" is acquired which promotes easy ascending. (e) This system is no better for starting than any other, so you can expect the usual "battle" to get underway until you have some weight from the rope. (f) Do not expect to get good with this setup overnight. Like all prusiking or ascending, it requires many adjustments and lots of practice. We don't claim it to be effortless, but we feel it is better than other common techniques...and we've given them all a fair trial. ("all" means five methods by their count; three by mine–R.T.) For ascending, the system provides a comfortable resting position with a minimum of backward leaning. The climber hangs nearly parallel to the rope, attached to it at chest level, but with his weight placed on his buttocks. Both legs do the lifting, so one foot fatigue does not occur. The right arm is the only "working arm," the left one is never raised beyond shoulder level. With the flexible rope linkages on the ascenders, it is possible to rotate them to switch hands if desired. However, the climber should not have to do this if he is using the system correctly.

I suspect that this method may not work against a slope, but never having tried it under these conditions, I cannot be sure.

(15) Mountain climbers occasionally use prusik-climbing techniques, but they regard it mostly as an emergency measure and do not use elaborate setups. Manning (1960) describes a system used for crevasse rescue. The foot slings pass around and behind the legs and through a waist loop, worn for belay purposes, to the standing rope. A chest sling is

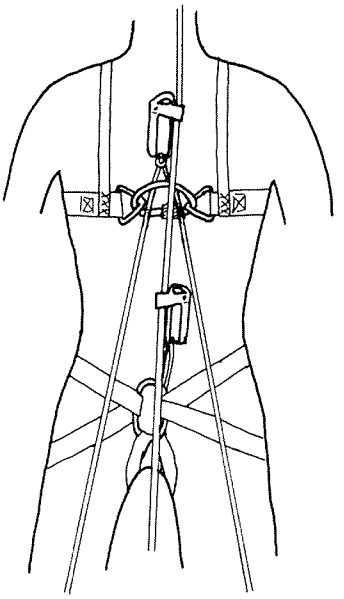


Fig. 64. The Wisconsin System. Separate chest and seat slings are shown for clarity in the illustration, but the original used a modified parachute harness.

also used. P.D. Smith (1960) suggests the use of foot slings only. He recommends prusiking on two parallel ropes as being easier than prusiking on a single rope. This procedure would not work on any but a very short drop.

(16) In this system the top knot is connected to a chest sling, and the lower knot is connected to both feet as in System 3. I have not tried or seen this system. I hear it is fast and strenuous. Besides the discomfort of hanging in a chest sling, the stomach muscles get tired. When both legs are lifted at the same time, the stomach muscles do all the work.

(17) This sytem uses a seat sling and a chest sling, with the right foot sling connected to the seat sling. A short sling connects the seat sling to the chest sling. The top knot is attached to the chest sling. The lower knot is attached to the left foot. The demonstration I saw ended in failure when the rig came apart. This method either requires one-legged lifting or depends on loosely tied seat and chest slings. I'm not quite sure about the effectiveness of this system.

(18) Seat and chest slings are used in this system also, with short rope connecting them. A carabiner is clipped around this rope and into an ascender. The other ascender is attached to the feet. The person using this system stands up and pushes his ascender as high as he can. Then he leans backward and the carabiner slides from his chest sling to his seat sling. The lower ascender is moved up. He then pulls himself up and forward with his arms as he stands up again. This method is reputed to be fast, but it requires a person with a compact build and strong arms to use it. The only advantage to this method seems to be a long gain per cycle.

(19) This one-knot method is used for emergencies only. Assume you have rappelled into a pit and have forgotten or lost your foot sling. Such things have been known to happen. Improvisation is called for. You could cut the end of your standing rope and make it into slings, but if there is not enough rope for a full set of slings, or if you do not want to damage your rope, you can rig a one-knot prusik. Double the rope back on itself, and with its free end tie a prusik knot in the standing part of the rope, leaving the free end on top. Attach your seat sling to this knot, using the free end of the rope. Double the standing rope back on itself to form a loop below the prusik knot. Hold this loop firmly in place with one hand, step in the loop, and raise yourself on one foot. At the same time, move the seat knot up with your other hand. Then, supporting your weight in the seat sling, lift your foot and pull the loop snug underneath it. The hand holding the loop will soon become tired. You could tie loop knots or more elaborate hitches around your foot to ease the effort of holding the loop. If there is enough rope on the bottom, you can tie two climbing knots and even a seat sling without cutting your rope.

General Comments on Prusiking

Two on a Rope. The best discussion of this practice is an article by Bill Cuddington (1966). The practice of two persons prusiking simultaneously on the same rope is best suited to long free drops. The two climbers should stay close together, so that the lower man will not be so greatly endangered if the top man dislodges a rock or some mud. At breakovers they can push out from the wall together. A short section of ladder is sometimes used so the bottom man can stand on it and give the top man a foot of slack. If one climber is using Jumars, he is usually put on top because he can negotiate the breakover more easily. The prusikers should be matched in speed so they can keep together. On short drops, the savings in climbing time does not offset the added difficulties encountered in keeping the same pace and going over the breakover. Two on a rope is not justified for most caves.

Several people report that the top climber has trouble with knots slipping. I suspect that this is due to the straightness of the standing rope. Normally a knot will bend the rope when it grips. The top man should either use mechanical ascenders, have one ready to clip on if necessary, or use knots with a great margin of holding power. The more effective emergency methods of stopping a downward

slip cannot be used with a person's weight on the rope below.

Breakovers. Prusiking over the edge of a pit is almost always a problem. Various solutions have been described. Some involve tying on an extra sling above the breakover. One of the foot slings can be used for this. Jumars can be removed and quickly re-attached above the breakover. If your body is above the knots, it is easier to push away from the wall. If the foot slings are fashioned from continuous loops, you can place your foot in the sling above the foot loop to raise your body. If the slings have eyes on a single rope, you can half-hitch them around your shoe. You can either push away from the wall or roll so that your body is between the wall and the standing rope. The more elaborate and sophisticated schemes either do not work under all conditions or take too much time. I find it quickest to just use force. I get my knots as high as I can, stand up, push away from the wall however I can, and slide my hand under the standing rope.

Speed. People are prusiking faster and faster. To give specific records in this article will assure quick obsolescence. People have already climbed 100 feet in less than a minute and have climbed out of Golondrinas in less than an hour. The fastest systems for racing are, in order: the Ropewalker, Mitchell method, Jumar system, and inchworm method. The average racing times for 100 feet using some of the older methods with knots are around 3 minutes. A speed of 8 to 12 feet per minute is normal for a good prusiker in a sustained climb under slightly less than optimum conditions. Speeds of 20 feet per minute are not uncommon, but the cavers who do this are both skilled and strong.

One hundred feet has been accepted as standard for prusik racing. It is a good choice. A shorter distance would test only skill at moving knots. Most climbers in the races I saw showed signs of tiring at 60 feet. A much longer climb would be a test of stamina only.

Popularity. For purposes of general information and as an aid to selection of a personal prusik system, I shall give the relative popularity of various materials, devices, and methods as I have observed them in the course of gathering information for this article. I make no claims for great accuracy since sampling was haphazard, some areas of the country were not represented, and the ranking is by feel. I am not at all sure what criteria to use for popularity. If I judge by the number of users of a given method, the many cavers who very seldom go into a vertical cave would dominate the results. In a nationwide survey, consideration of the Northeast, with its many cavers and a lack of deep pits, might give the result that ladders are most popular, whereas, in fact, they are almost never used by those who are in the forefront of vertical exploration in North America. Perhaps the distance climbed with each method should be the standard, but it can only be roughly guessed.

Type of knot or ascender:

1. prusik knot.
2. Jumar ascender
3. Gibbs climbing cams
4. rbs knot
5. Bachmann knot

The prusik knot and Jumar ascender are by far the most popular, and it is not clear which is really the most popular. The prusik knot is used by the beginner and occasional vertical caver for economy. Many cavers who want to increase their prusiking speed use Jumars. Some experts return to knots for a variety of reasons. The rbs knot is very popular in Pennsylvania. The Gibbs cams are commercially available.

Prusik system (the numbers in parentheses are those used to enumerate the systems in this article):

1. Texas prusik, one-legged (4)
2. Texas prusik, two-legged (3)
3. Classic three-knot system (1)
4. Plummer system (5)
5. Jumar system (6)

The Texas prusik (both methods) is used by beginners because of its simplicity and by experienced people because of its versatility. The three-knot system is used by old-timers who started with it and by younger cavers desiring a versatile system.

Sling material (for knot users):

1. Polypropylene
2. Polyethylene
3. Manila
4. Nylon

Beginning and Training

Prusiking, like many other skills, is best learned from an experienced teacher, rather than from a book. The main reason is that a demonstration is much better than a written description. A skilled teacher can diagnose difficulties instantly. There are many small motions used in prusiking that I have not described.

I would recommend that the beginner try either the classic three-knot prusik (1) or the Texas prusik (3 or 4). These are both versatile and proven systems. The three-knot system teaches the skills of balancing and pacing better than any other method. These skills can be transferred to any other method if the three-knot prusik is found not to be ideal. If the chest sling is uncomfortable, it should be made wider, looser, or repositioned. If there is still trouble with the chest sling, or if you are sensitive to chest pressure, the Texas prusik should be tried.

The Texas prusik is generally easier to teach. There are only two knots, and the only possible sequence of moves is to move one, then the other. The position of the legs is not critical.

Other systems can be taught, but they are generally more complicated in their rigging or movements, or they are not as versatile. I advise strongly against teaching a beginner to use mechanical ascenders. I feel that a person should be competent in the use of knots before he begins to use mechanical ascenders. This sounds like the eternal advice of old-timers regarding innovation, but I feel it is justified. There is no problem of unlearning old skills to learn the new method. Mechanical ascenders have not yet reached a state of perfection, although they are more uniform in their performance than knots. When mechanical ascenders fail, the only recourse is to use knots, whereas the holding power of a knot can always be improved by retying.

Individual Equipment

It is customary for vertical cavers to carry their own rappelling and prusiking equipment. There are very good reasons for this practice. It assures that each caver is thoroughly familiar with the equipment he uses. Passing equipment up and down pits is time consuming and sometimes difficult and hazardous. Experienced vertical cavers normally question the competency of one who does not have his own equipment. All too frequently a party of near-novices descends a pit with only one set of Jumars to be used by the entire party. The slings will be the wrong length for most of the party, but they will probably not know the difference. In one such case the first person up was unable to negotiate the breakover. Fortunately, another party was in the cave at the same time, and one of its members was able to help. In another case, the first two people down did not have ascending gear (What would they have done if they found their rope was too short?). and they were not able to render assistance when the next person got stuck while rappelling. Apparently this person did not have ascending gear either. In a cave register, I once read the note of a party of seven who were using a single set of Jumars. They were cold and tired of waiting. I can imagine the trouble they had with their gear landing on a ledge halfway down. It is customary for one person to attach his slings to the main rope while another person is climbing. The man on the bottom can usually stand to the side or under some cover to avoid possible falling rocks.

Greatly related to individual equipment is the custom of each person carrying his own gear up the drop. I have heard many say that they normally tie their equipment to the end of the rope and pull it up. Some groups, on the other hand, make it a strong point of cave etiquette to carry gear while prusiking. They have had too many packs get stuck when being hauled out. The other danger is that the combined weight of all the equipment may be very great--just try lifting eight cave packs.

The party gear, such as ropes, may or may not be hauled up, depending on how free the drop is.

Comfort

Avoiding fatigue is the most important factor in being comfortable while prusiking. When you are tired and hanging on a rope, every point of discomfort is painfully apparent. When you are fresh, you can easily ignore most of the discomforts. Being in good physical condition is important. Prusiking is one of the most strenuous forms of exercise. A beginner will usually get very tired because he will be fighting difficulties all the way. With more experience, he will develop an efficient system, and the same climbs will be less tiring. An occasional strong beginner will not be tired on any drop. The moderately experienced caver will have trouble pacing himself. I have found it best to climb at the fastest speed that can be sustained for the whole length of the climb. On a short drop this is as fast as I can go. The most common mistake on a longer drop is that of starting too fast. Then it is necessary to stop and rest, which is not very effective. Once one is tired, sitting in even the best seat sling is not comfortable. Unless I am very tired (as from struggling with poor knots), I find it best to continue at a reduced pace. Pausing for a breath after moving each knot provides some rest without any one position becoming uncomfortable.

No matter how cold you are at the bottom of the drop, you will warm up when you are climbing. The only exception is when there is ice water coming down the rope. In sub-freezing temperatures, it is hard to obtain a proper equilibrium body temperature, since part of you will be sweating while other parts are chilled. On a deep pit, most people remove their jackets and climb with only a single shirt to provide protection from the slings. Coveralls are less versatile than jackets.

The use of wide slings has been emphasized by many writers. In general, cavers in areas with the deepest pits use the widest slings and the most elaborate prusik rigs. The choice of sling width is a personal one. Weight must be balanced against comfort. Nerve pinching must be avoided entirely.

Women who prusik with a chest sling have a special problem. Some take care of the problem by using an extremely loose horse girth as a chest sling. Others use a high chest sling; or a very low, tight chest sling can be used. I have had no takers on an offer to design and build a combination bra and chest sling out of nylon webbing for any female caver who wants to use one.

Spinning and the resultant dizziness are not so common a problem as in the past with the increased use of braided ropes for long, free drops. However, even braided ropes can acquire a twist from vertical-wrap rappel devices, which is why these devices are little used now. Most people can tolerate spinning if they simply make up their minds to do so.

Safety

Prusiking is inherently safe in that there is no danger of falling off or becoming hopelessly stuck if a mistake is made. There are hazards, however, and everyone prusiking should be aware of them.

The most important part of any ascending system is the standing rope. A single standing rope is normally used. If it were to break, at best, a party could be stranded. At worst, someone could fall to his death. Consequently, the caving rope should be treated with great care. Ropes should be inspected frequently, usually as they are being lowered down a drop, or when the rope is being coiled afterward.

Manila rope is seldom used today. Its main disadvantage, and the reason it is seldom used, is that it can rot. Rotting can be retarded by drying the rope after each use, or by applying anti-rot chemical treatments, but the easiest way to avoid rotting is to use a synthetic rope. Still, manila is occasionally used. Some deep cave systems have been assaulted with the plan of abandoning ropes rather than hauling them out. Rescue groups often lose ropes and can save money by using manila. Large manila ropes have been used in jagged pits where cut resistance was important (Cud-

dington, 1965). For many years some old-timers used it for its handling qualities. The appearance of the inner fibers of a manila rope gives a good indication of the condition of the rope. An inspection of the inner fibers of a synthetic rope gives less information than does an inspection of a manila rope. The center of a braided rope cannot be inspected. A pull test can be given to both synthetic and manila ropes, with tension greater than any that would be exerted on the rope in normal use, about 500 lbs (Patten, 1966; Leonard and Wexler, 1946), and less than that which would damage the rope (more than 3,000 lbs can break the rope after a knot has been tied in it--Drummond et al., 1968). One thousand pounds is the load generally mentioned, but the exact force is not too important. Plummer (1960b) has described a crude dynamometer that can be used to judge the force when a car is used to do the pulling. The most common way of testing a rope is to have everyone in the party pull on it.

Rope padding is normally placed between the rope and rocks to protect the rope from abrasion. It also serves to keep the rope clean. The breakover at the top of a pit is the most critical point for padding. Sharp ledges can also damage the rope. The pads can be strips of any heavy material such as canvas or carpeting. Sections of hose that have been slit open have also been used, but are generally not as convenient. In extreme cases, to prevent sawing across a ledge, the standing rope has been rigged to bolts with short slings.

Prusik slings wear out faster than the standing rope. It is hard to decide when to replace prusik slings. A slightly frayed rope and a nearly worn-out rope look much alike. Many of us are miserly with rope or too lazy to be constantly making new slings. One safeguard against sling breakage is redundancy, which means that your body is attached to more than one knot or that your slings are firmly attached to your feet. A short line can be tied to the slings near the foot loop and its ends tied around the ankle. This takes time. Some faster ways have been devised. Hartline (1967) describes how to make a double adjustable foot loop with a prusik knot. Warren (1969) uses a loop of sewn webbing. The webbing loop should be just big enough to fit over the foot with boots off. The foot slings are run inside the loops. The loops are worn all through the cave. All of these methods have the same effect–if the sling running to your chest or seat breaks, you will find yourself hanging by your foot. From this position you must pull yourself upright and attach another sling to the rope. The spare sling must be easy to reach. I prefer to have an extra line running from my foot sling near the climbing knot (or ascender). If my upper knot breaks, I will not fall completely upside down.

A separate safety line is almost never used. In the early days of prusiking they were tried and soon abandoned. People quickly found out that single rope is the most trouble-free way of rigging. Two ropes invariably get twisted around each other. Ladders and safety ropes can also become entangled, but not as often or as severely. Fouling can be avoided if the ropes are rigged far apart, but with a narrow pit opening this is impossible. Also, the rope being dragged across the lip of the pit can dislodge rocks upon the prusiker. Rappel-prusik techniques were condemned in their early days because of the lack of a separate safety line. Continued use demonstrated that, in competent hands, the techniques could be safe. The growing acceptance of rappel-prusik techniques eventually quieted most critics.

There is still an occasional criticism of prusiking on safety grounds. Various mishaps and the difficulty of learning proper technique are pointed out. Ladders are claimed to be much better for the average caver or for routine caving. Most of the mishaps, which are of the sort covered in this safety section, can be blamed on insufficient training or experience. What is routine depends on the caving group and their caving area. For some, drops of several hundred feet are routine. A caver who does only one short drop a year might not want to take the time to learn prusiking. For him, ladders would be the best choice. It is generally conceded, however, that ladders are better for extremely bad situations, such as going through a waterfall.

A knot that is marginal in its holding

power can often be made to hold by setting it by hand. If this fails, the sling must be retied with a better holding knot or replaced. If knots are found to slip at the start of a climb, the changeover process is relatively simple. If this happens when you are on the rope, the process is much more hazardous and difficult. Usually all knots do not fail at the same time. You must then hang by your other knots while you retie or replace the bad one. If it is a foot sling that slips, there is no trouble in hanging from the knot supporting the body. If you have only one knot to your seat or chest sling and that is slipping, you have a difficult problem. You must attach a new sling to support your body while you are holding onto the standing rope for balance. You must have the spare sling with you where you can reach it easily. You can either use the new sling for prusiking or use it only for support while retying the old one in a manner that will hold better. Bill Cuddington carried a Jumar attached to his seat sling and would clip it on quickly. Since he did not use the Jumar for anything else, it was not worn out or clogged with mud, and therefore was not likely to slip.

If all your knots slip at once, the first thing to do, of course, is to try to stop. You can do this by bending the rope upward below the knots. If all else fails, grab the rope beneath you and slip into a body rappel. It will be hard to do this if someone is prusiking on the rope beneath you. This is one of the reasons why two on a rope can be hazardous.

When Jumars slip, there is no way to augment their holding power. For this reason, the slings that I attach to my Jumars can be removed and tied into prusik knots.

Although jamming knots and fatigue are not usually considered a mortal danger, they have caused one death--that of James Mitchell, who was unable to ascend a waterfall in a New York cave in 1965. Having knots jam is usually a cause of exertion, fatigue, and cursing. On occasion I have rigged into a hardware rappel, gone back down, and changed slings when my knots jammed, but usually I just fight my way to the top.

I know of four instances of ropes having been eaten by animals. Only one of these cases was reported in a newsletter, indicating that there may be more unreported. In the one case that has been reported, at Valhalla Pit, Alabama, the animals were probably attracted by garbage that the cavers left at the top of the drop. The only ways of avoiding this hazard are the use of cable ladders or the stationing of rope watchers.

I have not heard of anyone burning through either the standing rope or his prusik slings with a carbide lamp flame, but there have been cases of scorching. Cavers are generally aware of this hazard. Most of them get into the habit of making their motions so that the flame stays well away from the rope. Some use electric light for prusiking, and a few prusik in darkness.

If I were to use any one standard to judge the ability of a vertical caver, it would not be his speed or the depth of the pit he has visited, but his ability to cope with emergencies. The better vertical cavers I know use a rig that will work under almost all conditions. They spend time practicing switching back and forth between rappel and prusik. If their knots slip, they know how to tie a knot with greater holding power. If something breaks, they have something else holding them to the standing rope, and the replacement part is where they can reach it. They spend time thinking up possible difficulties and how to overcome them. They may use mechanical ascenders, but they can use knots of any sling material if necessary.

The "Final System"

This chapter has covered most of the prusik systems in use. No system or method has been recommended as "best." "Best," ultimately, must be judged in terms of what is best for a particular individual. This means you must experiment and get the feel of various techniques and materials. The many small motions, the coordination, and the balance cannot be described in words.

The methods described here include most of those in use. I still hear of new techniques, and to be all-inclusive would mean that this

chapter would never be printed. Some of the finer points, such as methods of connecting the various components of a prusiking rig, have been entirely left out. Many of the methods are regional in popularity. I hope that this will encourage versatility of vertical techniques. The traditional inventiveness of cavers should produce some interesting developments in vertical caving in the future.

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APPENDIX A

The following four pages are copies of the earliest articles on prusiking to appear in United States caving publications. The publication's cover is reproduced below.

CUMBERLAND GROTTO

NATIONAL SPELEOLOGICAL SOCIETY

TECHNICALIA

Contents: THE GOOFAH.....A Cave Boat

ROPE NOTES

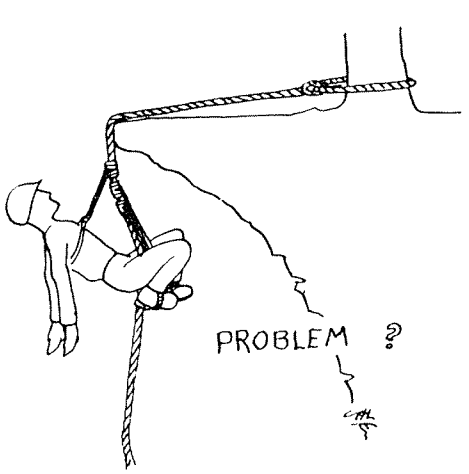
by

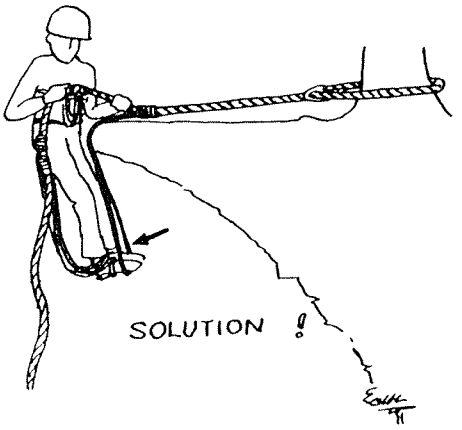
D. Bloxsom

and

C. Link

April 10, 1956





ROPE NOTES

This lad is in trouble. Sure, he can get over the edge, but it will require a terrific effort. Dan Bloxsom leaves a short loop sling just above the edge, for a hand hold. Now we know that an edge like this is no problem if we have foot holds and can relieve the tension on the rope at the edge.

So - let us convert the short hand sling to a long foot sling, tied to the rope above the edge. Then simply stand in the sling and pass all three climbing knots up the now slack rope past the edge.

The climber here to the right could not find toe holds, and could not push himself far enough off the edge to pass up his knots.

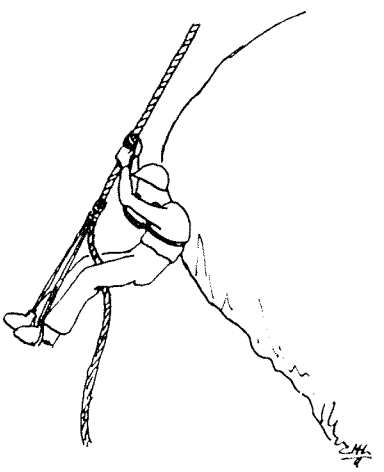
But he could get his shoulders against the rock and extend his feet far enough to get the rope off the edge.

So now he is passing his chest knot up past the edge.

He's practically up.

This is more difficult than above.

C.H.Link, Jr.

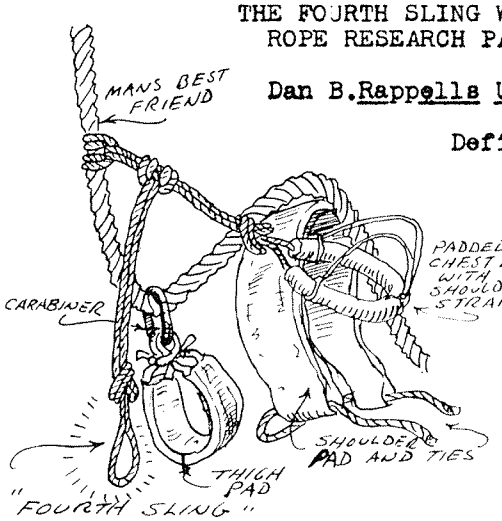


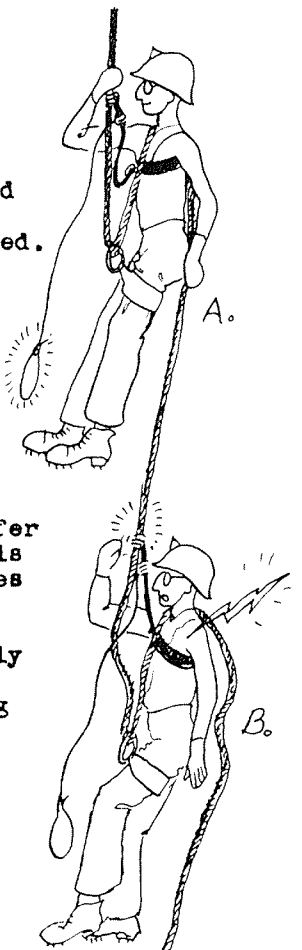
ROPE NOTES
THE FOURTH SLING WORKS AGAIN
ROPE RESEARCH PAYS OFF

Dan B. Rappells Up Rope!

Defies Gravity!

Guaranteed, Tested, and Demon - strated.





The gear developed to make rappelling safer easier and more comfortable, by Dan Bloxsom, is sketched above. On the right shows how Dan uses the chest prussic knot as an auto-safety, and how the fourth sling gets him back into the rappell after a stop. He is rappelling normally at A; stops at B, with or without shock; and at C he steps into the fourth sling. Standing up in the sling at D; he recovers the rappell at E; holds the rappell while kicking off all weight from the auto-safety at F, taking all weight on the rappell and he is back at the first condition, A. By alternating through positions CDECDE he moves up the rope!

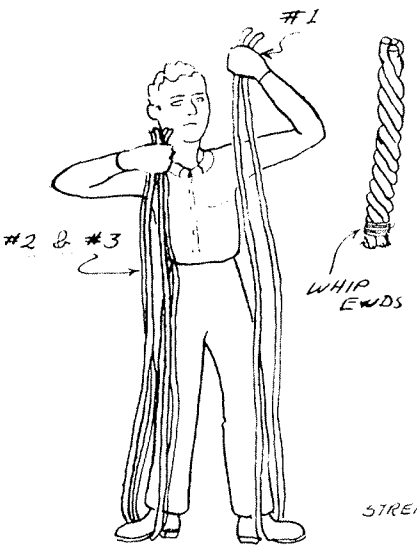
Step B need not occur. One may stop at any time and go into position D, to rest and cool off, or just to look around. The Fourth Sling was first introduced in the Troglodyte for June 1955, as an aid in prussic knotting over edges. Here again it provides the needed foothold. - CHL.

6

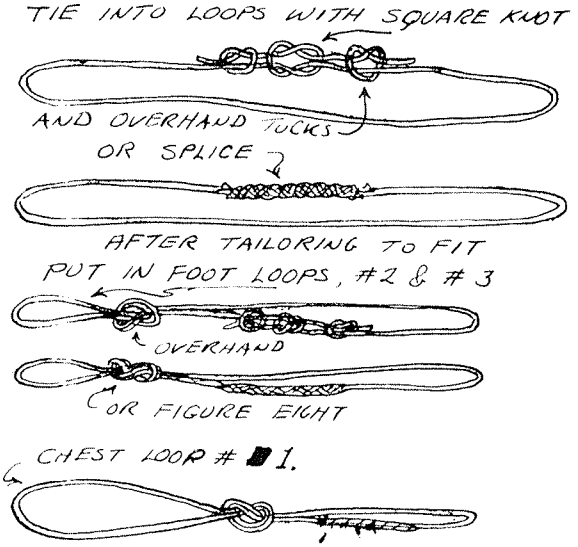
MAKING THE PRUSSIC KNOTS

USE 3/8" MANILA, 1350 POUNDS TEST

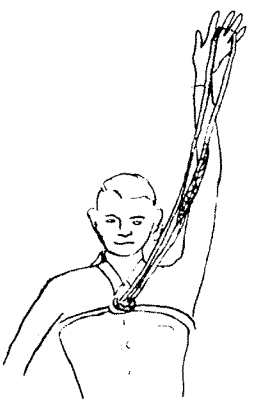
MEASURING THE ROPES



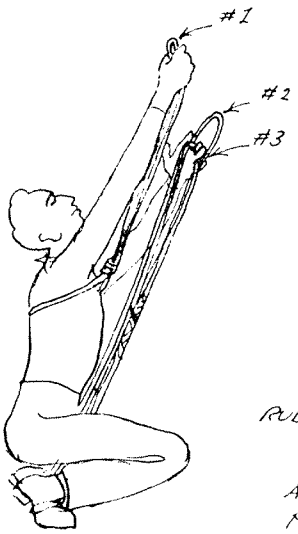
TIE INTO LOOPS WITH SQUARE KNOT



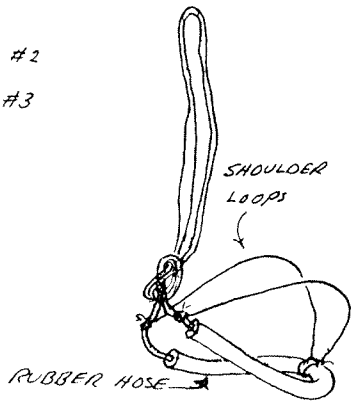
STRENGTH OF {KNOT / SPLICE} IS {60% / 90%} of ROPE.



TAILOR CHEST KNOT LIKE THIS



TAILOR FOOT LOOPS LIKE THIS



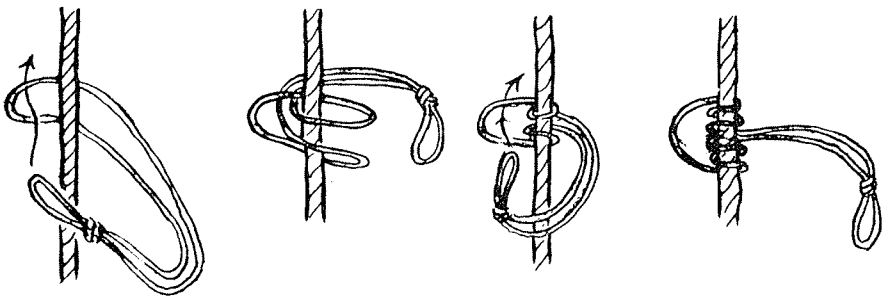
FOR COMFORT AND CONVENIENCE PAD LOOP AND ADD SHOULDER STRAPS

Make up THE FOURTH SLING IN FORM OF #2 & #3 BUT AS LONG AS #1. It has SEVERAL USES.*

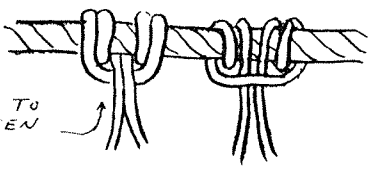
FOOT LOOPS SHOULD FIT TIGHTLY OVER SHOES. CHL,

* SEE ELSEWHERE IN THIS ISSUE AND IN JUNE 1955 TROGLODYTE.

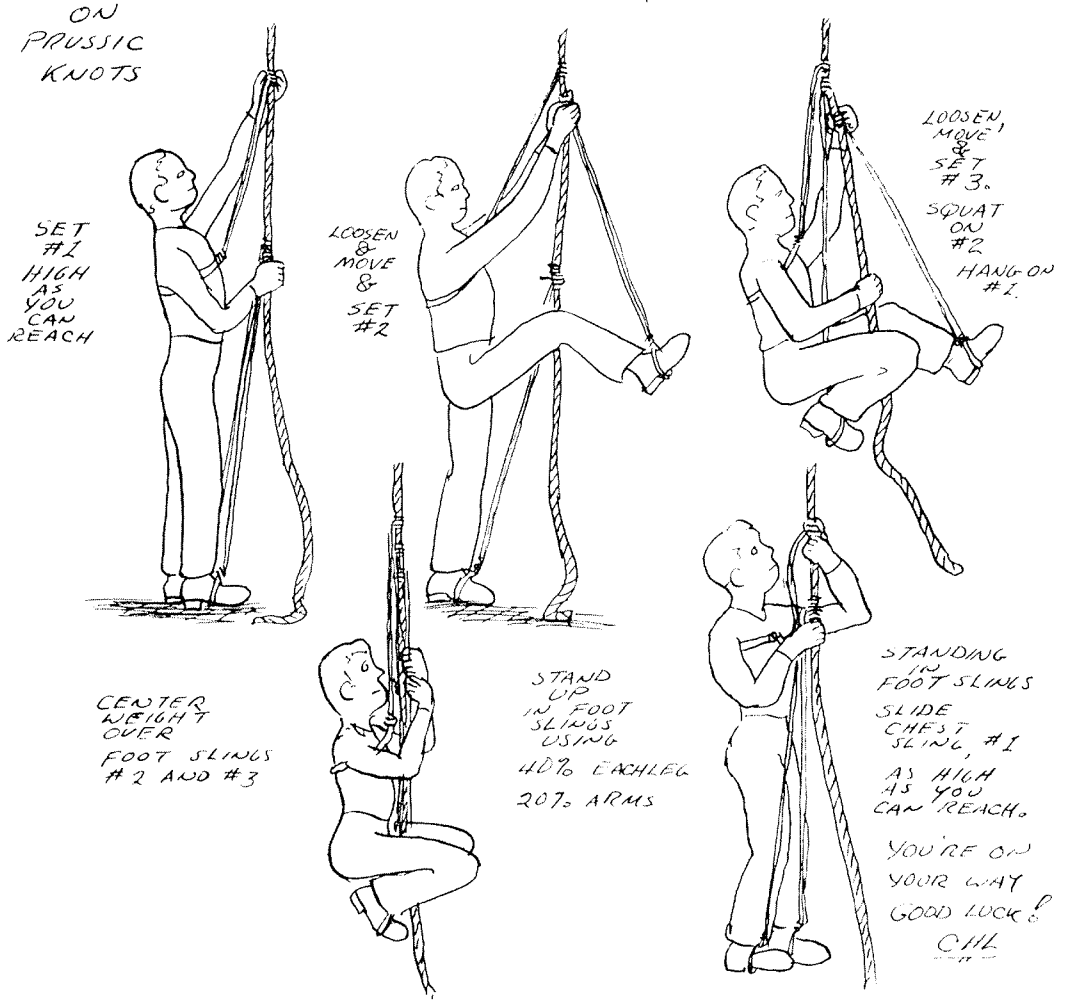
USING THE PRUSSIC KNOTS



TYING THE PRUSSIC KNOT



CLIMBING ON PRUSSIC KNOTS



APPENDIX B

THEORY OF THE CLIMBING KNOT

By William T. Plummer

Abstract

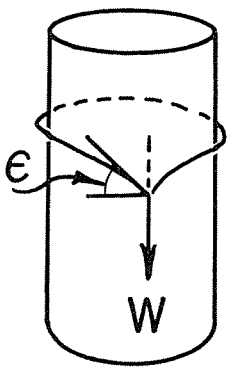
Starting from simplest ideas a mathematical study leads to a quantitative result for the holding power of a climbing knot. Application is made for the case of the prusik knot and for a few other knots in use. A new knot is presented which will hold on any rope, no matter how slippery. Considerations governing the choice of sling material are derived. It is found that a slippery rope is most easily climbed with slippery slings.

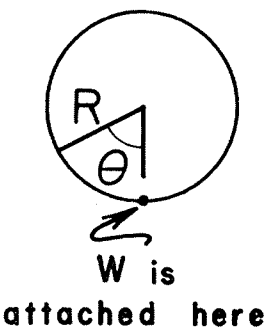
Treatment of a Fixed Loop

The following simplifications are made. The validity of each will be discussed later.

1. The main rope is replaced by a smooth, rigid cylinder.
2. The sling material is completely limp and weightless, but is rigid with respect to a twist about its axis.
3. The sling rope is of much smaller diameter than the rope which is to be climbed.

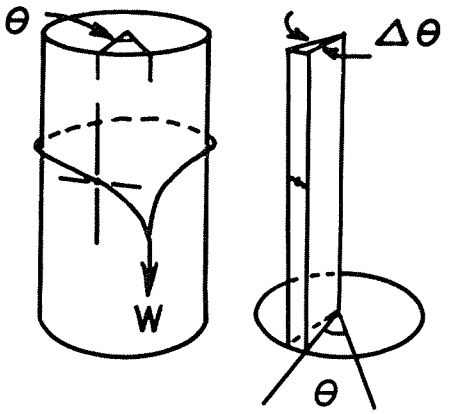
Let us consider the very simplest sort of "knot" which could be used. This is a fixed loop of cord a little larger than the cylinder. When such a loop supports weight W, the point of support will be a cusp in the loop. Both branches will lie at some angle ϵ above the horizontal. The actual curve formed by the loop is more complicated than it looks, but may be found. It will be shown that a loop larger than a definite size will not grip the cylinder, but a loop of any smaller size will. This critical loop size may be characterized by its angle, ϵ.

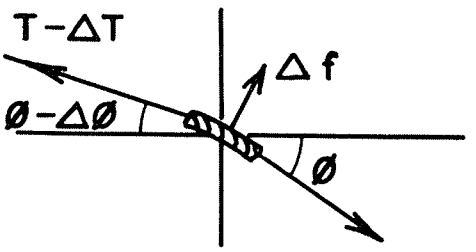




We have to use some kind of coordinate system. Looking down on the cylinder, the angle θ designates a direction out from the center. We may let θ be zero at the point where the weight W is supported, and it will then equal π radians (or 180°) around back at the most distant point. By stating a value for θ, we refer to a particular point on the loop.

One other angle which is important is the tilt of the sling rope, the loop, at each value of θ. We see that this angle, ϕ, is equal to ϵ at $\theta=0$, and decreases to 0 at $\theta=\pi$, around back where the sling loop is horizontal.



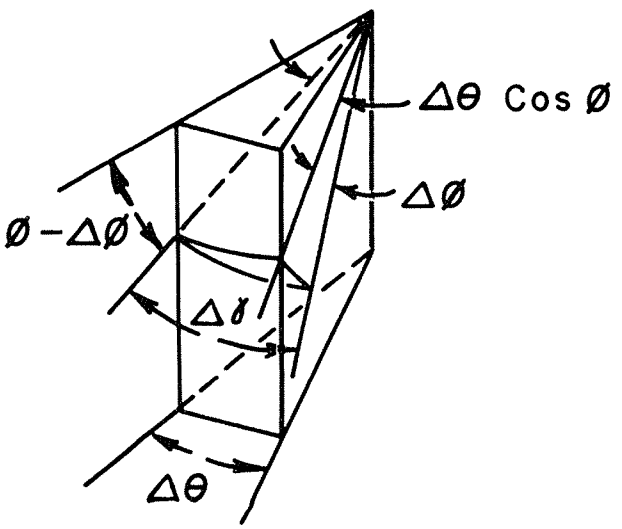


Now look at a very short segment of the loop, at an arbitrary position θ. The little piece extends across a small angle $\Delta\theta$ as shown. We may draw a set of axes right at the segment and show its form. The tensions upon its ends are T and T-ΔT, acting at the angles named. The quantity ΔT is the change in tension from one end of the little piece to the other, and $\Delta\phi$ is the change in tilt from one end to the other. Since the segment is short, both changes may be considered very small.

In the plane tangent to the cylinder at the position θ, there is a force Δf which is perpendicular to the sling and accounts for the curvature ΔT and Δf are in this plane. To find the values of ΔT and Δf we must approach the problem a little differently.

In general a short element of the loop may be represented as a small arc of a circle. This arc, at any point of the loop, will determine a "plane of curvature." In general, this plane is *not* the same as the plane tangent to the cylinder. In the next few steps we shall find the true plane of curvature at an arbitrary θ.

In the plane of the arc, the angle between the directions of the ends of the element is $\Delta\gamma$. With a little solid geometry, we find that:

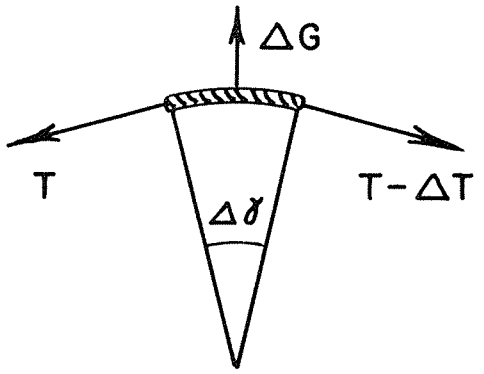


$$(\Delta\gamma)^2 = (\Delta\theta)^2 \cos^2\phi + (\Delta\phi)^2$$

$$\Delta\gamma = \sqrt{(\Delta\theta)^2 \cos^2\phi + (\Delta\phi)^2}$$

or $$\Delta\gamma = \sqrt{\cos^2\phi + \left(\frac{d\phi}{d\theta}\right)^2}\ \Delta\theta$$

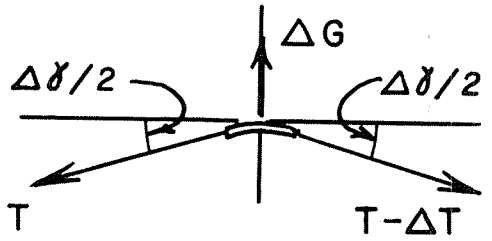
Then in the plane of curvature, we have a situation like this: Here ΔG is the force that is perpendicular to the element of the loop and causes the curvature $\Delta\gamma$.



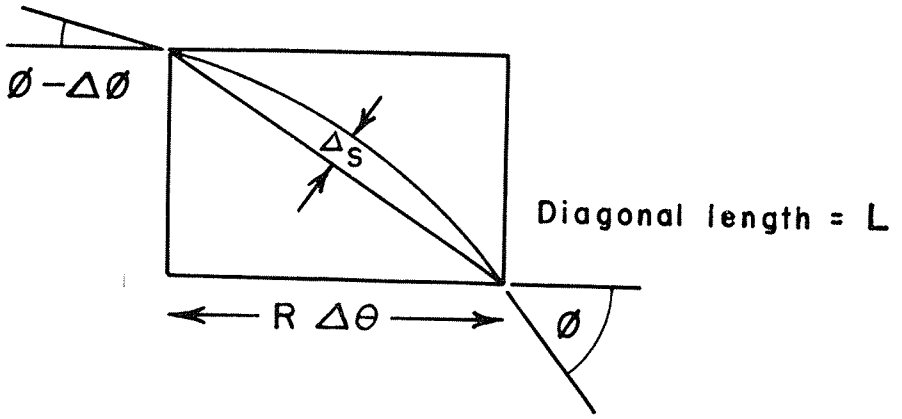
We have seen how $\Delta\gamma$ is related to $\Delta\theta$ and $\Delta\phi$. For the small angle $\Delta\gamma$, we may calculate ΔG easily from the force diagram. Since ΔT is very small,

$$\Delta G \doteq 2T \sin(\Delta\gamma/2) \doteq T(\Delta\gamma)$$

$$\Delta G \doteq T\sqrt{\cos^2\phi + \left(\frac{d\phi}{d\theta}\right)^2}\ \Delta\theta$$



The force ΔG is perpendicular to the segment of the loop, but may not be perpendicular to the surface of the cylinder. To find its direction, we need more solid geometry. Let's flatten out a little rectangular piece of the cylinder, of width $R\Delta\theta$ and just high enough to contain the little piece of the sling loop.



The diagonal of the rectangle is drawn. The separation Δs between the loop and the diagonal may be found by letting the arc be part of a circle, and noting that $\Delta\phi$ is small.

The radius of a curvature of the arc in this *flattened* area is:

$$\mathcal{R} = \frac{-L}{\Delta\phi} = \frac{-R\,\Delta\theta}{\cos\phi\,\Delta\phi}$$

$$\Delta s = \mathcal{R}(1-\cos\frac{\Delta\phi}{2})$$

$$\cos\frac{\Delta\phi}{2} = 1-1/2(\frac{\Delta\phi}{2})^2 + \text{ ...smaller terms.}$$

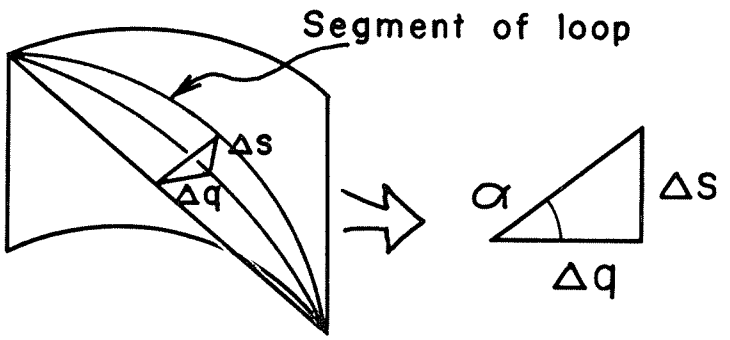
$$1-\cos\frac{\Delta\phi}{2} \doteq 1/2(\frac{\Delta\phi}{2})^2$$

$$\boxed{\Delta s = (1/2)\,\mathcal{R}(\frac{\Delta\phi}{2})^2 = \frac{-R(\Delta\theta)(\Delta\phi)}{8\cos\phi}}$$

Now put the rectangle back on the cylinder and roll it into its original shape. It will bow outward somewhat, by the amount

$$\Delta q = (1/2)\,R(\frac{\Delta\theta}{z})^2 = \frac{R(\Delta\theta)^2}{8}$$

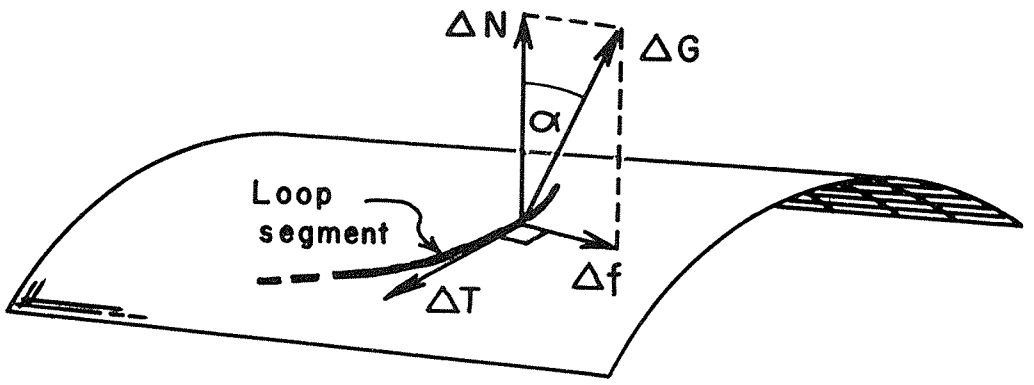
Let us see what the rectangle looks like back in its position:



We get a little right triangle as indicated, when we draw a new straight line connecting the corners of the bent rectangle. This new line lies in the true plane of curvature of the short piece of loop. And more important, the angle α is just the angle between this plane of curvature and the local perpendicular to the cylindrical surface. We see that

$$\tan\alpha = \frac{\Delta s}{\Delta q} = \frac{-R(\Delta\theta)(\Delta\phi)}{8\cos\phi}\;\frac{8}{R(\Delta\theta)^2} \quad \tan\alpha = \frac{-1}{\cos\phi}(\frac{d\phi}{d\theta})$$

Now we may resolve ΔG, the force perpendicular to the loop segment in its plane of curvature, into two components, which will be perpendicular and parallel to the cylinder. These components appear as ΔN and Δf, respectively, in the diagram below.



Both Δf and ΔT are in the plane tangent to the cylinder. But ΔN is perpendicular to this plane. The resultant force *in* the plane is the vector sum of Δf and ΔT, and has the magnitude:

$$\sqrt{(\Delta f)^2 + (\Delta T)^2} \leqslant \mu(\Delta N);\ \mu = \text{coefficient of friction}$$

With the proper substitutions this equation will specify the form of the entire sling loop. Since we had

$$\Delta f = \Delta G \sin \alpha$$

$$\Delta N = \Delta G \cos \alpha$$

$$\Delta G = T(\Delta \gamma) = T\sqrt{\cos^2 \theta + (\frac{d\phi}{d\theta})^2}\ \Delta\theta$$

The last equation becomes, after substituting for these three quantities and squaring,

$$T^2[\cos^2\phi + (\frac{d\phi}{d\theta})^2](\Delta\theta)^2 \sin^2\alpha + (\Delta T)^2 \leqslant \mu^2\ T^2[\cos^2\phi + (\frac{d\phi}{d\theta})^2](\Delta\theta)^2 \cos^2\alpha$$

We divide through by T^2 and solve for $(\Delta T/T)^2$, and get

$$(\frac{\Delta T}{T})^2 \leqslant [\mu^2 \cos^2\alpha - \sin^2\alpha][\cos^2\phi + (\frac{d\phi}{d\theta})^2](\Delta\theta)^2$$

$$0 \geqslant \frac{\Delta T}{T} \geqslant -\sqrt{(\mu^2 + 1)\cos^2\alpha - 1}\ \sqrt{\cos^2\phi + (\frac{d\phi}{d\theta})^2}\ (\Delta\theta)$$

This differential equation cannot yet be integrated to give T as a function of θ, because ϕ is an unknown function of θ. In fact, ϕ may not be uniquely determined by θ, so it may be possible for the loop to have a range of shapes, and still not slip. We are interested in only the worst case, however; the point at which the loop just fails to hold. For small values of μ, corresponding to a slippery cylinder, the first radical becomes imaginary. The second radical is always real. Since it is not physically possible for $\Delta T/T$ to be imaginary, the equation shows us the value of μ for which the loop slips.

To keep $\Delta T/T$ real, so that the loop holds, we must set

$$(\mu^2 + 1)\cos^2\alpha - 1 \geqslant 0$$

We note that $\Delta T/T$ is zero for the value of μ which makes this expression zero. Thus a loop at the point of slipping has the same tension all the way around the cylinder. This is a way of saying that the loop has arranged itself so that all available friction is used to prevent slippage, and none is used to change the tension from place to place.

We may write the same expression as

$$\frac{1}{\cos^2\alpha} \leqslant \mu^2 + 1$$

From geometry

$$\frac{1}{\cos^2\alpha} \equiv \tan^2\alpha + 1, \text{ for any } \alpha$$

But

$$\tan\alpha = \frac{-1}{\cos\phi}\left(\frac{d\phi}{d\theta}\right)$$

Then

$$\frac{1}{\cos^2\phi}\left(\frac{d\phi}{d\theta}\right)^2 \leqslant \mu^2, \quad \text{or} \quad \boxed{\mu \geqslant \frac{1}{\cos\phi}\left(\frac{d\phi}{d\theta}\right) \geqslant -\mu}$$

Right at the point of slipping there is a unique case:

$$\frac{1}{\cos^2\phi}\left(\frac{d\phi}{d\theta}\right) = \sec\phi\left(\frac{d\phi}{d\theta}\right) = -\mu$$

or

$$\boxed{\sec\phi\, d\theta = -\mu\, d\theta}$$

This is the differential equation for the shape of the loop just at the point of slipping. It may be integrated immediately.

The result is

$$\log\tan\left(\frac{\pi}{4} + \frac{\phi}{2}\right) + C = -\mu\theta$$

To determine the unknown constant, C, we use the fact that the sling is horizontal ($\phi=0$) around back where $\theta=\pi$.

Then

$$\log \tan \left(\frac{\pi}{4} + 0\right) + C = -\mu\pi$$

But

$$\tan \frac{\pi}{4} = 1, \text{ and } \log 1 = 0$$

Therefore

$$C = -\mu\pi$$

The equation for ϕ becomes

$$\log \tan \left(\frac{\pi}{4} + \frac{\phi}{2}\right) = \mu(\pi - \theta)$$

Or we may write

$$\boxed{\tan \left(\frac{\pi}{4} + \frac{\theta}{2}\right) = e^{\mu(\pi-\theta)}}$$

Or equivalently

$$\sin \phi = \tanh \left[\mu(\pi - \theta)\right]$$

With this expression for ϕ, it is straightforward to obtain the length of the loop by one more integration. The result is

$$\mathcal{L} = 2R \frac{\sinh \mu\pi}{\mu}$$

We will merely note that as μ becomes small, the loop length must approach the cylinder's circumference as a limit, in order to hold.

For our main purpose, we will apply the shape equation to the special point at $\theta=0$, to find the limit $\phi=\epsilon$. Since ϵ is a maximum at the point of slipping, a loop with any value smaller than this will hold. Thus we get

$$\boxed{\tan \left(\frac{\pi}{4} + \frac{\epsilon}{2}\right) \leqslant e^{\mu\pi}}$$

or $\sin \epsilon \leqslant \tanh \mu\pi$

The transcendental equation just written gives either

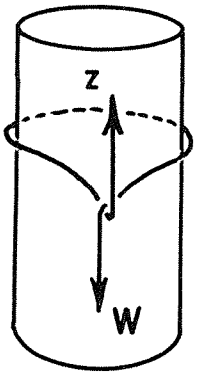
1. The maximum allowable angle ϵ for a given coefficient of friction μ.
2. The minimum allowable friction μ for a specified junction angle ϵ.

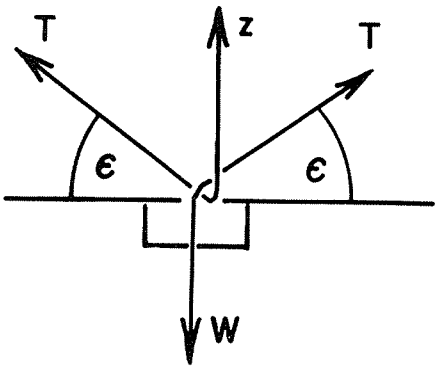
If the fixed loop were of smaller size, or if μ were larger, then ϕ would not be a unique function of θ. Thus we might deform the loop to some slightly different shape, and it would still hold. But we are interested in the limit at which the knot just *fails* to hold. The importance of this case will become apparent as we make use of the results found so far.

To do more, we must introduce some more facts about the physical situation. Instead of a fixed loop, we will consider a single half-hitch on the cylinder. We will find the equilibrium value of ϵ for the half-hitch, and will compare it with the value found above to determine when the half-hitch is stable.

Treatment of a Single Half-Hitch

To keep a single half-hitch from pulling open, we must apply the tension z at the top, in a manner not yet specified. It is not hard to show that z is less than W, and to find the value which ϵ will assume for this case. It will be noted that the knot will change its shape until a stable value of ϵ is found, and then the previous discussion will indicate whether the hitch will slip on the cylinder.





In equilibrium at the junction, the horizontal components of the tensions are equal and opposite. The vertical components will balance, too, when

$$z + 2T \sin \epsilon = W$$

So that the lower sling rope will not slip through the junction, we must have

$$T = We^{\frac{\mu_s}{\sqrt{2}}\left(\frac{\pi}{2} - \epsilon\right)}$$

(This is just the formula for snubbing around a cylinder. The factor $1/\sqrt{2}$ appears because the lighter rope crosses itself at an angle of 45° at the bend, regardless of ϵ, and $\cos 45° = 1/\sqrt{2}$.) The new coefficient of friction μ_s is for sling rope against *itself*, rather than against the cylinder, and μ_s need not equal μ.

There is a third condition for equilibrium. So that the upper sling rope will not slip through the junction, we use the snubbing formula again and find

$$z = Te^{\frac{-\mu_s}{\sqrt{2}}(\frac{\pi}{2} + \epsilon)}$$

When we put these last three equations together, we get

$$Te^{\frac{-\mu_s}{\sqrt{2}}(\frac{\pi}{2} + \epsilon)} = z = w[1-2(\sin\epsilon)e^{\frac{-\mu_s}{\sqrt{2}}(\frac{\pi}{2} - \epsilon)}]$$

We see that

$$\frac{z}{w} = [1 - 2(\sin\epsilon)e^{\frac{-\mu_s}{\sqrt{2}}(\frac{\pi}{2} - \epsilon)}] = \frac{1}{r}$$

For all permissible pairs of ϵ and μ_s, the fraction $1/r$ is less than one. Thus the tension W below the knot has been reduced by the ratio r above the knot, to z. We'll come back to this.

Using the rest of the equation above, and replacing T by its value in terms of W, we get

$$We^{\frac{-\mu_2}{\sqrt{2}}(\frac{\pi}{2} - \epsilon)}e^{\frac{-\mu_s}{\sqrt{2}}(\frac{\pi}{2} + \epsilon)} = w[1 - 2(\sin\epsilon)e^{\frac{-\mu_s}{\sqrt{2}}(\frac{\pi}{2} - \epsilon)}]$$

Divide out the W's and simplify.

$$e^{\frac{-\mu_s\pi}{\sqrt{2}}} = [1 - 2(\sin\epsilon)e^{\frac{-\mu_s}{\sqrt{2}}(\frac{\pi}{2} - \epsilon)}]$$

Solve for

$$(\sin\epsilon)\, e^{\frac{-\mu_s\epsilon}{\sqrt{2}}} = \frac{1 - e^{\frac{-\mu_s\pi}{\sqrt{2}}}}{2e^{\frac{-\mu_s\pi}{\sqrt{2}}}} = \frac{1}{2}[e^{\frac{+\mu_s\pi}{2\sqrt{2}}} - e^{\frac{-\mu_s\pi}{2\sqrt{2}}}]$$

Or we could write

$$\boxed{(\sin\epsilon)\, e^{\frac{-\mu_s\epsilon}{\sqrt{2}}} = \sinh(\frac{\mu_s\pi}{2\sqrt{2}})}$$

This last equation specifies the single value of ϵ which is permitted for any chosen sling friction μ_s. The sling will slip on itself until this angle develops.

Application of Equations to the Simplest Knot

We have found two transcendental equations for the half-hitch:

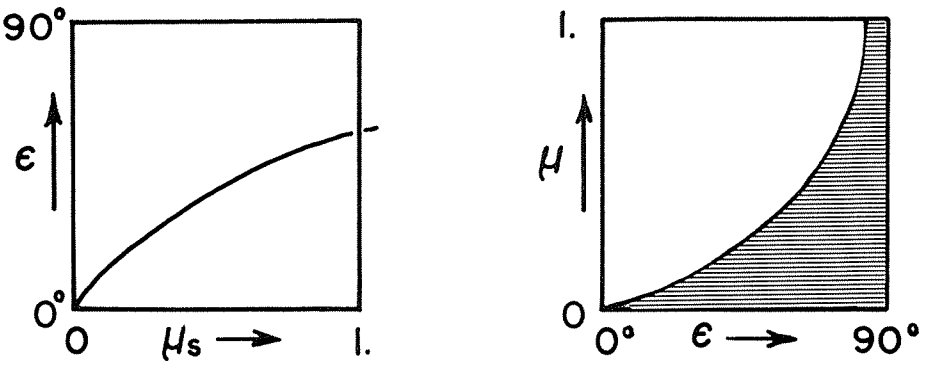
$$(1)\quad \tan(\frac{\pi}{4} + \frac{\epsilon}{2}) \leqslant e^{\mu\pi}$$

$$(2)\ (\sin\epsilon)e^{\frac{\mu_s\epsilon}{\sqrt{2}}} = \sinh(\frac{\mu_s\pi}{2\sqrt{2}})$$

The first tells the lowest μ we may have with a given ϵ, and the second tells us what ϵ will actually be for a given sling friction μ_S. So starting with knowledge of μ_S for the sling material, we could find ϵ by one equation, and then learn the lowest possible μ from the other equation. That would be the slippery limit for gripping a cylinder.

Transcendental equations cannot be solved in ordinary ways. Usually it is easiest to solve them graphically.

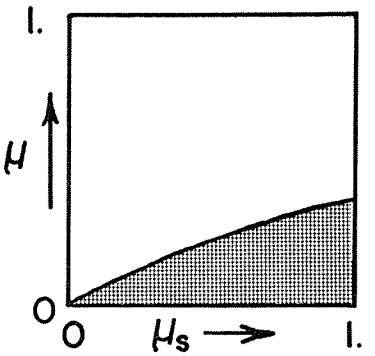
Putting the second equation first, we get the following pair of graphs for the solutions. (These were obtained with the help of preliminary graphs.)



The shaded region indicates prohibited values. Values above it are allowed.

To use these graphs you pick a sling friction μ_S, read the first graph to find the angle ϵ at which the knot will form, and then find this ϵ on the second graph to find the range of permitted values of μ.

In fact, the graphs may be combined so that this information is found in one step. The result is



The curve is remarkably close to a straight line in this region! Now under the condition that a sling alone is characterized by μ_S, and that μ is a joint property of your sling and the rope you want to climb, the condition we have found may be stated simply as:

μ_S must be *less* than 3μ

So to climb slippery rope, it will actually be to your advantage to use slippery slings! This is the reason why new slings are easier to use than old, rougher ones.

Discussion

At first glance it appears rather easy to be sure that μ_S is less than 3μ, just by using slings of the same material as the rope you are climbing. But it is not that simple because μ_S is the coefficient of *static* friction between two parts of the sling, and μ is the coefficient of *moving* friction between the sling and the rope you are climbing. After all, you want to *stop* after your knot has slipped a little. Since static friction may easily be two or three times as great as sliding friction, the condition derived may not be easy to meet.

But before we all go back to climbing ladders we should ask *why* certain values of μ are prohibited, and what happens if we should try to use one.

If your slings are too rough for a particular climb, the knots won't be self-adjusting. This is the difficulty. You could still make the climb, perhaps, by tightening a knot with your fingers each time you let go of it, but the knot wouldn't automatically constrict when you put weight on it. Beyond a second critical value of μ, however, your climbing knot will not stay sufficiently snug even after being tightened by hand, and slippage will take place.

With dry ropes it is almost impossible to fail to meet the condition on μ_S and μ. Observed values of μ_S range from 0.28 for new nylon to 0.89 for well-used manila. Values of μ, measured while moving, range from 0.26 for new manila on new nylon to about 0.65 for old manila on old manila. All of these combinations meet the condition, so observed difficulties in using dry climbing knots on dry ropes are caused entirely by knot stiffness rather than any failure to satisfy the friction requirements.

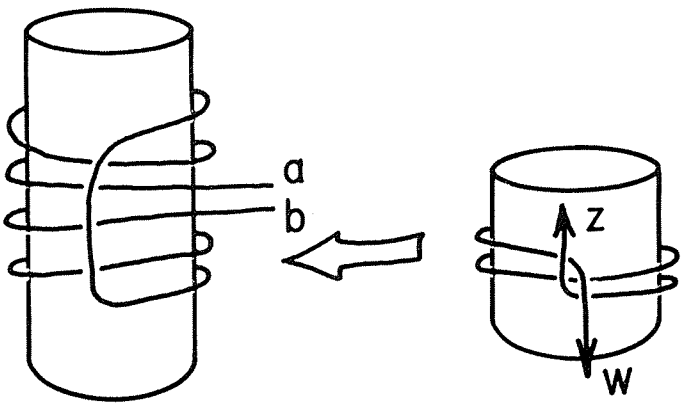
The condition we have derived can easily be made to fail on a main rope coated with mud. The problem is not at all simple, because mud comes in all concentrations, and very dilute mud may actually increase the friction, μ, and make the climbing knot hold tighter. What generally happens, however, is that the film of mud on the main rope develops into a polished surface, with very low μ. If the mud has affected the sling rope to a lesser extent, or in a different manner because of a different composition, then μ may become less than $\mu_S/3$. Now measurements show that μ_S for a manila sling rope will decrease somewhat as the rope is broken in, and then increase. Its lowest value will be about 0.3 for a fresh sling which has been used only enough to lose its stiffness, and the highest value will be about 0.9 for a veteran sling with rough surfaces and plenty of caked dirt. This range indicates that over the course of its lifetime, the absolute holding power of a manila sling will decrease by a factor of three, and near the end it will be capable of holding only clean ropes without help.

From the figures given, nylon would appear to be a good sling material because it is slippery on the surface. But there is a major disadvantage to it. When tension is applied the nylon stretches, and the knot tightens. When tension is removed the nylon shortens and swells. The swelling of the nylon makes most climbing knots tend to jam. In addition, nylon is a little too limp and is more trouble to slide upward. There is need for a strong, slippery, but non-elastic rope material for slings. If your patience is adequate, you may find nylon climbing knots useful for climbing a very muddy rope, when manila knots won't hold. Otherwise, they are a nuisance.

Application to Higher Knots

Now that we have seen how internal friction can affect the holding power of a knot, it shouldn't be surprising that most of the popular climbing knots represent the various ways of getting around this difficulty. Each can be understood a little better in light of the calculation for the half-hitch.

The most familiar and most dependable climbing knot is the prusik knot. The lower half of it is much like the half-hitch we have been discussing, except that there is an extra turn.

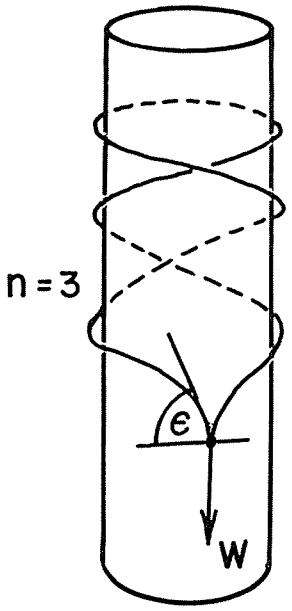


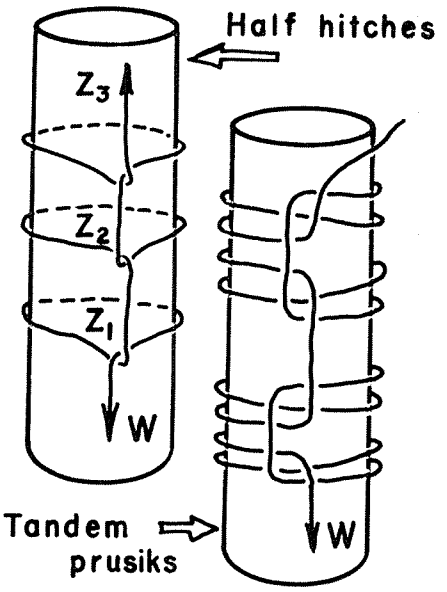
As before, z is less than W by a ratio controlled exponentially by μ. With the two loops the ratio is approximately $R=r^2$, since the tension at the top of the first loop is diminished again by the same ratio. (A third loop would not, however, be much improvement.) We find that the ratio R is increased by some other features as well. Where the vertical parts meet, there is some pinching of the inner turn against the main rope. The part of the knot connecting upper and lower halves serves two purposes. First, it provides the tension z, arising from the drag of the upper two turns on the main rope. Second, it pulls all four turns together to make ϵ *smaller than the value it would have with a half-hitch in equilibrium.* When this happens, the condition on μ becomes less demanding, and it is possible to climb on a more slippery rope. (see graph of μ against ϵ.)

If you have trouble making a prusik knot grip, it will help to adjust things to increase the tension in the lower part of the knot (b) and decrease the tension in the upper part (a). In fact, the upper end (a) could just as well be entirely loose.

Another climbing knot sometimes used is formed by wrapping the sling around the main rope in a criss-crossing fashion. In this case we refer back to the treatment of the fixed loop. Angle ϵ is determined as soon as this climbing knot is tied, and then the minimum permissible value of μ may be obtained from the first of the differential equations. In this case ϕ will be zero not for $\theta=\pi$, but for θ equal to some odd multiple of π. In the picture, ϕ is zero when $\theta=3$. Thus μ cannot be found directly from the graph. But we see from the equation that μ is effectively multiplied by n when the sling encircles the main rope (or the cylinder) n times, as compared with the single fixed loop first studied. There are then two important advantages: a rather small value of ϵ may be used in each turn, and μ is multiplied by the number of turns. Since the holding power is exponential in μ, the holding power of a knot with n turns will go roughly as r^n. I say "roughly" because the sling will tend to stick to itself at the points of crossing, and will not readily conform to the most efficient shape. This knot can lose its form more easily than a prusik knot would, and it may slip unexpectedly.

Other knots have been constructed on this general design, some having the sling rope doubled as it winds around the main rope. Because the knot is loose and open, it may be tied with some types of nylon sling material without extreme jamming.





A while ago the ratio

$$\frac{z}{w} = 1 - 2(\sin\epsilon)\, e^{\frac{-\mu_s}{\sqrt{2}}\left(\frac{\pi}{2} - \epsilon\right)} = \frac{1}{r}$$

was derived for the half-hitch. Now in the unhappy limit when μ_s and μ are very small, ϵ also will be small. We may then say approximately,

$$\epsilon \doteq \mu\pi, \quad \sin\epsilon \doteq \epsilon \doteq \mu\pi$$

$$\mu_s \doteq 2\sqrt{2\mu}, \quad e^{\frac{-\mu_s}{\sqrt{2}}\left(\frac{\pi}{2} - \epsilon\right)} \doteq e^{-2\mu\left(\frac{\pi}{2} - \mu\pi\right)} \doteq 1 - \mu\pi$$

$$\frac{1}{r} = 1 - 2\mu\pi(1 - \mu\pi) = 1 - 2\mu\pi + \frac{4\mu^2\pi^2}{2} \doteq e^{-2\pi\mu}$$

$$\boxed{\frac{z}{w} \doteq e^{-2\pi\mu} < 1}$$

We now see that the ratio z/W is less than one for any possible μ. The form of the last expression happens to be identical to the familiar snubbing formula. The tension reduction with the half-hitch, in the limit when μ is made small, is just the reduction which would be found if a length of sling rope were snubbed one full turn (2π) around the main rope (or cylinder).

If we now set up several half-hitches in tandem, then

$$\frac{1}{r} = \frac{z_1}{w} = \frac{z_2}{z_1} = \frac{z_3}{z_2} = \cdots = \frac{z_n}{z_{n-1}}$$

Thus with n half-hitches, the ratio obtained is the product of these, or

$$\frac{z_n}{w} = \left(\frac{1}{r}\right)^n = e^{-2\pi\mu n} = \frac{1}{R}$$

Even with a small value of μ, the product ($n\mu$) may be large enough so that the knot holds well. All we have to do is find a way to provide that final small tension z_n at the top, so that the total knot will keep its shape. This is done just by adding one more half-hitch. The drag it provides will be enough, if the necessary z_n has been made small. To get rid of the upper end, *entwine* it with the loop of the last half-hitch. Do NOT tie it to the lower end of the sling, as a pull on the *top* of the knot can cause it to slip.

As a practical suggestion, make alternate half-hitches mirror images of each other, to cancel out their tendency to twist on the rope. When this is done, the knot will keep its shape well.

Try this knot sometime when you are experimenting with ropes. It may save you the shame of a rescue someday when your main rope is muddy and nothing else will hold. It is less convenient to use than a prusik knot, and takes up more room, but by adding turns, you can make it grip *anything*.

Along this line, two prusik knots properly tied in tandem will hold on nearly anything. The upper end is just left free. (See next page.) In a typical case the drag provided by the upper half of a prusik knot may be only one pound. If the ratio of a half-knot is R=20, then the entire knot might support only 20 pounds. But two knots in tandem would support 1x20x20x20, or 8000 pounds. The rope would break before the knots could slip!

Either of these combination knots, the running half-hitch or the tandem prusik knot, could eliminate most of the vertical cave rescues made necessary by slippery ropes. I've used the tandem prusik knots to climb a 30-foot piece of brand new quarter inch nylon rope, with slings made of 3/8-inch manila. The knots were in no danger of slipping: they were even a little hard to move.

In these cases we gain remarkable gripping power by making use of the fact that the mechanical advantage of climbing knot is multiplicative, and not merely additive.

As with all aspects of vertical rigging, it is a good idea to try out knots like these while you are above ground. Learn what they will do for you, and what their limitations are, before you use them in a cave.

The assumptions made initially are worth a short note. First, we called the main rope a smooth, rigid cylinder. Its lack of rigidity and its structure will be of some help in holding a climbing knot. The depression of the rope under the constriction of the knot will increase μ. Second, the sling material was considered to be ideally limp, weightless, and non-twisting. Its weight is negligible, and each popular knot design is arranged to cancel the effects of twisting. You recall that in the running half-hitch, the alternate loops are made mirror images of each other for this purpose. But it is well known that sling rope is not very limp, until has been "broken in". If the sling is stiff, it will not contact well along the entire angle assumed, and the result will be a decrease in the effective value of μ, and perhaps a loss of grip. The stiffness begins to become important when you bend the sling rope about a radius comparable to its own. To avoid this, use a sling rope a size or two smaller than your main rope, so that the bending radius is proportionately larger. Both 5/16-inch and 3/8-inch slings work well on 1/2-inch rope.

The stiffness consideration does not change the discussion of the half-hitch where it crosses itself, for there the ropes cross at 45°, and the effective radius of bending is twice the radius of the rope. In any case, a little stiffness would be an advantage here.

There isn't space to discuss the method of prusik climbing, and our concern has been entirely with knots which can be used. The method has been developed to great efficiency, and is actually easier than ladder climbing over a long distance. The central idea is to balance properly so that your legs do all the work of climbing and your arms do almost nothing. This efficiency requires slings of exactly the right lengths *for you*, and these may be calculated from the formulas in the June 1962 NSS NEWS, page 70. Other information may be found in back issues of the *Baltimore Grotto News* or the January 1966 NSS BULLETIN.

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