

The Study of Knot Performance

Exploring the Secrets of Knotted Cordage to Understand How Knots Work

Introduction to the Study of Knot Performance

We do not know half of all there is to be discovered about knots.

– Geoffrey Budworth, *Knots and Crime*

Under the circumstances, it behooves the layman to speak skeptically rather than dogmatically about why knots behave the way they do.

– Cyrus Lawrence Day

For all puzzles there is always a beautiful solution.

– Harold S. M. Caxeter

When Thor asked the mayor why he had never before revealed the secret of hauling the moai upright, he replied, “Nobody asked me.”

– Thor Heyerdahl
Kon-Tiki Man 166

Knots were among the first practical devices created by human beings and one of the few primitive inventions we continue to use. They are part of our common humanity. Surprisingly, few people show much interest in them or how they work.

– aak

People tie knots, use them, teach them, but rarely stop to analyze them.

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Summary of these Studies of Knot Performance

The characteristic that distinguishes knots from other objects created by mankind is their structure. Analysis of the structure of several familiar knots and how they bring to bear mechanical forces reveals the devices that determine their performance. From this analysis, answers are emerging to the question “How does a knot work?”

Knots work by creating friction between intertwined strands of rope. They fail to work in three ways: when they slip apart under a normal load, when they deform and slip apart under an abnormal load, and when they break under an excessive load. By examining how particular structures of knots harness universal mechanical forces, we can come to understand the factors that make knots hold together and those that cause them fail.

The original studies of knot performance collected here lead you to an understanding of how any kind of knot works. They show you

- How to use the step-by-step procedures of structural analysis to examine the structure of knots.
- How to understand the elementary principles of mechanics that affect knot performance.
- How to understand the interaction of structure and mechanics that makes a particular knot behave the way it does.
- How to examine the three essential properties of practical knots, their security, their stability, and their strength; and, as part of the background to the study of knot strength, how to examine the breaking point of knots.

The focus throughout these studies is on the interaction of mechanical forces with the structure of knots tied in standard materials and applied in uniform conditions. Some of these studies pertain only to knots tied in ropes made of natural materials, but many of the concepts and procedures apply to all knots. Although the results of the studies can be useful for analyzing the various ways to tie knots and to use them in rope systems, they are not directly concerned with these skills.

Learning these techniques for analyzing knots can develop your concepts of knot performance, improve your selection and use of knots, and increase your knot safety.

The Neglect of Knot Performance

Anyone who drives an automobile probably knows more about what goes under the hood of a car than inside a knot. Even many people who depend on knots to support life or heavy loads fail to take an interest in their inner workings. The way they function often seems as mysterious as a computer, where the mechanisms are complex and hidden from view. While the structures that make knots perform the way they do are simple and open for all to see, they have become so familiar and commonplace that we usually fail to notice them. In addition, they interact in subtle ways. Because few people have asked how knots work or have devised fruitful ways to study them, their inner workings are little understood.

As far as I have discovered, no one has previously developed a systematic method for analyzing the structure and mechanics of a knot to determine its holding properties, and no one has presented a general explanation of how knots work and why they behave the way they do.

In developing these studies during the past several years, I have been surprised that so few people are aware of how a knot works. Even among persons who depend on knots for supporting life and loads, the study of knot performance is often neglected. Inquiring about the essential characteristics of knots has not become part of habitual patterns of thought. When I describe the procedures and results of my studies of knot performance, the usual response—even from experienced knot users who are engineers—is, “I had never thought of that.”

Studying the Four Aspects of Knot Performance

These paper move toward answers to several questions about knots that have often been neglected:

1. The Security of Practical Knots

- How do a Bowline or a Double Fisherman's Knot perform under a normal load?
- Can you tell whether a knot is secure just by examining and analyzing it?
- Of common knots, which are the most secure? What structures make them secure? How do these structures work?

2. Knot Stability

The study of knot stability focuses attention on the distinction between *stability* and *security*. These two aspects of knot performance are frequently confused and even more frequently entirely ignored.

- How does a particular knot behave when subjected to an abnormal load?
- How does deformation of a knot's structure lead to failure?
- Which common knots are the most stable? What makes them stable?
- How can the instability of a knot be used for a desirable purpose?
- How does the stability of a knot affect its security? Can a knot be secure but unstable?

3. The Breaking Point of Knots

- When placed under an excessive load, a Bowline tied in a rope made of natural fiber usually breaks at a point just outside the knot. Why does it break there?
- Under an excessive load, where does a Double Fisherman's Knot tied in the same natural-fiber rope usually break? Why does it break there?
- Can the findings about natural-fiber ropes be applied directly to artificial-fiber rope? Or do they have to be adapted? Or abandoned?
- Are there general principles that determine where any knotted rope will break?

4. The Strength of Knots

- What have tests shown about the comparative strength of knots?
- What structures make some knots stronger than others?

Finding answers to these questions entails close examination and analysis of several knots against a background of other writings.

Aims of these Knot Studies

The current studies focus on only a few practical knots tied in rope made of natural fibers and used in standard conditions. For this reason, the procedures and concepts developed here apply only in a limited way to knots tied in other materials and used in different conditions.

The long-range aim is to develop a set of concepts and procedures to discover fundamental principles that apply to all practical knots tied in any material under any conditions of use and in any atmosphere. These studies attempt to lead in that direction, however distant the goal may be.

Many of the procedures can be applied to the study of individual knots regardless of the materials or conditions. Their chief value for these kinds of knots may well be that they draw attention to aspects of knots that are usually overlooked and provide a way to study them. In this way, they help to arouse interest in knot performance and to extend the boundaries of our understanding.

Values of these Studies

These studies contribute to our understanding of knot performance in several ways. They

- Emphasize knot performance, an aspect of knot study that is poorly understood and often neglected.
- Bring together what is known about knot performance and present the results of an original examination of the relation between knot structure and mechanics and knot performance.
- Provide a method for estimating how well a knot will perform.
- Analyze a few familiar knots to help knot users understand the way that any practical knot works and how it fails to work.
- Supplement what we have learned about knots from tests and from experience.
- Help to raise awareness of the way knots work and to develop habitual ways of thinking about them.
- Reduce the risk of using knots for life support.
- Demonstrate a way to discover general principles of knot performance.
- Develop hypotheses that can be demonstrated and tested further.
- Provide concepts and appropriate terminology to facilitate discussion among people who use knots and those who study them.
- Suggest several questions and lines of thinking for further study of the properties of knots.
- Suggest principles that can be used for more scientific and technical study of knot performance.
- Provide a conceptual basis for further research.

In addition to these practical applications, a valuable effect of this kind of knot study is to increase our wonder at knots. Although their structure and performance are usually overlooked by people who use them daily, they are marvelous little devices.

Terminology Used in these Studies

I have found it necessary to introduce several new terms and to narrow or re-define several others. All of the terms used in these studies are explained in the separate paper on terminology as well as in the individual studies.

How to Read these Studies: Singly or in Sequence

These studies are arranged in a sequence that builds a comprehensive scheme for studying knot performance, but each paper can be read without reference to the others. To make the individual studies intelligible, I have repeated some of the key concepts and terminology.

The Expanded Point of View Developed by these Studies

The focus in these studies of knot performance is on a systematic way of thinking about knots which is based primarily on observation and analysis. The study focuses on *how a knot works* rather than *how to tie it* or *how to use it*. The analysis leads to conclusions about the performance of individual knots, but the general aim is to show how to use procedures that lead to the conclusions, not only the conclusions themselves.

People usually think about knots in two ways, 1) how to tie them, 2) how to use them. These studies on knot performance include these two ways of thinking but focus on a third: knots are devices that can be analyzed into their functional parts to see how they work.

Consider how learning about knots is like the typical stages of learning about driving a car.

1. Learning to tie a knot is like learning the location and function of the instruments of a car, the gear shift lever, the steering wheel, the brake pedal, and so on. You're not actually driving, but you're preparing to by becoming acquainted with how to manipulate the controls.

2. Learning to use a knot in practical applications is like learning to drive a car. You learn skill at steering, signaling direction change, accelerating, and braking. You also learn how to follow the rules of safety and motor vehicle laws. You can pass your driver education course and get your license.

3. Learning to understand how a knot works is like learning what goes on under the hood of a car, in the engine, the gear box, the differential. Few people become knowledgeable about how a car works, fewer how to repair it or make it perform better. Fewer still learn that sort of thing about the knots they tie and use. In fact, I have found very few people who have thought much about the matter.

The discussion on the next page shows how structural analysis goes beyond the traditional ways of thinking about knots and builds new concepts.

Expanding Our Ways of Thinking About Knots

Despite the introduction of numerous inventions that replace knots, knot use appears to be alive and well around the world. But what's missing in almost every case I have observed is an interest in understanding how they work—what makes them secure and stable, where they break, and what causes some to be stronger than others.

These studies on knot performance develop *a new and broader way of thinking* about knots. Consider how we can develop new perspectives on learning knotting skills:

1. Beginning Learners Think of Knots as Ways of Tying.

The main interest of anyone learning to tie knots, from a Cub Scout to an adult candidate for a rescue squad, lies mainly in learning the procedures for tying a particular knot. Most of the instruction found in knot books, on the web, and in training courses is about *how to tie knots*. This is, of course, the first and basic skill. But few people seem to get beyond that stage.

2. More Advanced Learners Think of Knots as Applications.

At a more advanced stage of learning, a student's range of vision broadens and interest shifts to learning how to use the knot for a specific purpose or application—perhaps by tying a Timber Hitch to move a heavy log or to tie a Prussic Hitch for lowering a litter from a mountainside. At this stage, includes interest in mastering the procedures of knot tying continues, but moves beyond that perspective to focus also on an application of the knot.

At this level, Scouts and rescue workers share the way of thinking with mountaineers, arborists, ski patrollers, sailors, and the dozens of other users of practical knots. The applications range from practical uses around the house to recreation and professional uses.

3. The New Perspective: Think of How Knots Perform.

At the most advanced stage of learning about knots, we bring *the way knots work* to the center of our attention.

Each stage of learning about knots adds a perspective on knots that engages the mind in a different way. Rope no longer remains just a piece of rope but becomes the material for tying a knot and using it to perform a task. Pretty soon, these ways of thinking become habitual.

As a matter of fact, at every stage of learning and in every application, knot performance has been at the heart of the knot-tying experience. A beginning learner ties a Square Knot, then pulls on the ends to see that it holds. A candidate for the Merit Badge uses the Taut-Line Hitch to pitch a tent. A rock climber hitches in with a Figure Eight Loop. But few people seem to have noticed the performance of the device they have created and tested and used.

We can add a new dimension to our knotting skills by applying the principles and techniques of structural analysis to study knot performance – this new aspect of knot study

Be sure to notice that we do not abandon skill at tying individual knots nor do we cease to use them skillfully in applications. By no means. But we broaden our point of view and cultivate new understanding. The remarkable fact is that beginners, even small children, can develop all three of these perspectives simultaneously, right from the start.

The Limitations of these Studies

Large areas of knot study remain beyond the scope of these studies. It is important to recognize that I have deliberately adopted several limitations to devise a project that could be reasonably managed.

A full understanding of the way a knot works would take into account all of the factors that affect knot performance. But we can more easily study the interplay of the first two factors, structure and mechanical forces, while holding constant the other two. This means that for the moment, we disregard the effect of various materials, uses, and weather.

Limitation of the Selection of Knots and Their Uses

I have made several assumptions about the knots themselves.

- I have examined only a few well-known knots.
- All of the knots are properly tied, arranged, and tightened, and the ropes are of uniform thickness and condition.
- Except as otherwise noted, I assume that the amount of load, rate of loading, and period of loading remain constant and that the knots are loaded in the standard way—a Bowline, for example, with the standing part anchored at the top and the load well distributed on the loop.
- I do not take into account the effect of backup knots because backups obscure the characteristics I want to expose and examine.

Limitation of the Materials

- The most important limitation of these studies concerns the type of cordage. While the range of materials that knots are tied in is virtually limitless, I assume that the knots studied here are tied in rope made of natural fibers. This means, of course, that the conclusions do not apply simply or directly to knots tied in rope made of artificial fibers or of other types of cordage. This limitation is especially important in the discussion of the breaking point of knots tied in climbing and rescue work. As is well known, ropes made of artificial fibers behave in very different ways from those made of natural fibers. But I have found it feasible to examine only one set of variables, and leave for later study the analysis of other variables such as the properties of different types of cordage.
- I assume that the rope is not deformed in any way that would hinder the motion of surfaces in contact.

Limitation of Environmental Conditions

- The knots are used in standard environmental conditions. I do not take into account the effect of varied conditions of temperature or humidity or of lubricants on the bearing surfaces of the rope.

Limitations of Scope and Method of these Studies

- This inquiry is limited to two aspects of knot performance, the knot's structure and the mechanical principles that come into play when a load is placed upon it. Other factors that affect performance are held constant.

- I have applied only elementary principles of mechanics.
- I have examined the interplay of structure and mechanical forces by means of observation and analysis alone.
- The study is guided by a series of procedures, but it does not make use of specialized technical knowledge, simulations, controlled laboratory tests, or numerical calculations.

At times, the discussion is based on meager evidence. This is because so few studies about knot performance have been published and I have not conducted original laboratory research.

The Method of Studying Knot Performance

The Method of Structural Analysis

Structural analysis is a series of procedures that reveal how the structure of a knot affects its performance. It uses the techniques of reverse engineering, that is, taking a completed device apart systematically to see how it works. In these procedures, we examine the way the segments of rope are intertwined so that they produce sufficient friction to keep the knot from slipping apart and coming untied. The aim is to raise awareness of the relation between the way a knot is built and the way it performs.

Structural analysis focuses our attention on basic questions about the inner mechanisms in a particular knot. How is it built? What mechanical principles come into play? How do the structural devices work together to create friction and make a knot secure? Under a normal load, how does the knot effectively resist slipping apart? How does it behave under an abnormal load? The result is a set of concepts that can be applied to any practical knot.

By supplementing the results of tests, the recommendations of experts, and our own personal experience, this kind of examination of the shape and function of the parts of a knot helps us develop new understanding of knot performance.

Development of the Procedures of Structural Analysis

I have developed the procedures of structural analysis over the past several years. I began to investigate the performance of knots by posing questions about how knots work, reviewing the knotting literature, and devising a set of step-by-step procedures for observing individual knots and for analyzing their structure and determining their mechanics.

Analysis of a few knots led to conjectures and surmises about their behavior, which then led to further analysis and tentative conclusions. As I developed the procedures in interviews with dozens of knot users, I sharpened and refined the questions and my conclusions. My own understanding has been enlarged through these interviews and through correspondence with persons knowledgeable about knots. The method of structural analysis is described in full in the study titled “Knot Security,” and it is applied in all of these studies.

The Method of Structural Analysis

The procedures used here for analyzing the structure and performance of knots are similar to those used in systematic inquiry of any kind:

- Begin by stating presuppositions and known or assumed general principles.
- Identify a research question to guide the inquiry; define terms and state the problem precisely.

- Limit the inquiry to manageable proportions by holding some variables constant.
- Select a specimen for analysis.
- Develop a series of increasingly clear and logical steps; using these steps, examine the specimen, both its parts and their function.
- Describe the parts and functions in detail; look for relations among parts and functions.
- Search for specific properties of the specimen and for universal principles that apply generally.
- Proceed systematically toward conclusions; state and record observations at each stage of observation and analysis.
- Synthesize your observations; drawing on intuition, make a conjecture about the way the specimen works.
- Check the conjecture by using the procedures to study other specimens and comparing the results.
- Record your revised conclusions.
- Have the whole project reviewed by outsiders.

The Utility of these Studies

Structural analysis supplements the knowledge and understanding about knot behavior that we have accumulated through testing and experience. It can correct some false and misleading concepts. It can enrich knot instruction by raising awareness of the way knots work and helping knot users judge the performance of these important tools. It can help to reduce the risk of using knots. It provides terminology, procedures, and concepts useful for further research and discussion among knot users.

Structural analysis is a useful technique for knot study because it

- Raises pointed questions about knot behavior
- Challenges some traditional assumptions about the way knots behave
- Clarifies concepts and procedures for studying knots
- Defines and uses standardized terms
- Develops a disciplined method of inquiry
- Produces a set of conclusions that can be re-tested and verified or modified, then abandoned or adopted.
- Develops curiosity on the one hand and habits of observation and analysis on the other
- Suggests directions for further study.

Who Can Benefit from these Studies

This method of study was originally designed for persons who use life-support and load-bearing knots, serious knot users such as climbers, ski patrollers, cavers, rope rescue personnel, ropes course managers, anglers, sailors, and so on. It was also designed for teachers and students of knot tying.

But this method has far wider practical use. As described here, the procedures of structural analysis may seem daunting at first. But they require only an ability to observe, follow procedures, and apply elementary principles such as load, pressure, and curvature. Both the procedures and the concepts can be widely understood because they are stated in ordinary language, using no statistics, formulas, graphs, or diagrams. For these reasons, the study of knot performance can be undertaken by persons without specific technical training, and it is beneficial at every level of knot use and knot instruction, from rank beginner to professional. I have used the procedures with evident success with small children as well as with mountain guides.

Reception of these Ideas

Many persons who have followed the systematic procedures of structural analysis have commented that this form of guided knot study increased their understanding. Some procedures challenged their assumptions about knots and made them aware of avenues for studying concepts that had remained obscure. Other procedures brought to the level of awareness ideas they had felt intuitively but had not thought of consciously or verbalized. It appears that within the limitations of scope of the inquiry, the procedures bring about the stated aims.

Although there has been little criticism of the procedures themselves, some of my conclusions about knot behavior expressed in earlier versions of these studies have not been universally accepted. Some of these conclusions have been challenged on the grounds that they do not apply to types of rope commonly in use and that they fail to take into account some important mechanical principles.

In this revised version of knot studies on allaboutknots.com, I have tried to meet these criticisms by refining the method of inquiry, making clear the limitations of scope, correcting some errors, and making my statements clearer. While I have considered all of the changes that correspondents have suggested, I have not adopted some of them. I continue to work toward more complete analysis and accurate conclusions.

Plans for the Future

Although I offer only tentative conclusions, a reliable understanding of knot performance seems to be emerging. And although some of the conclusions do not apply directly to other aspects of knots, I am confident that the procedures lead to a greater understanding of the way all knots work. If these studies can fill in some blanks in thinking about knot performance and suggest avenues for further study, they will have filled their main purpose. While all of the conclusions developed here have been carefully considered, they remain open for further study.

Application of the Procedures of Structural Analysis

Principles as significant as the ones discovered by the procedures of structural analysis ought not to be neglected. Both the procedures and the principles ought to be adapted for use in every lesson in knot tying. They ought to be applied habitually, and every insight gained by this analysis ought to influence daily decisions about ropes and knots, whether for utility or for life support.