14

ANCHOR PHYSICS

INTRODUCTION

This chapter is about some of the physical principles involved in building anchor systems. It is not intended to be an in-depth mathematical study of forces, although we will refer to some numbers. It is intended to present a common sense way of looking at the forces that are or may be involved in an anchor system, both when the system is working as intended and when all or part of the system fails. It is also intended to present easy-to-follow guidelines to use in constructing an anchor system that is least likely to fail.

BASIC DEFINITIONS

A **static system** is one in which all forces are in equilibrium, or one in which nothing is moving. An anchor system set over the side of a cliff for climbing is a static anchor system.

A **dynamic system** is one in which some forces are not in equilibrium, resulting in movement in some part of the system. An anchor system set over the side of a cliff for climbing starts out as a static anchor system, but becomes dynamic when the climber falls. The weight of the climber causes the climbing rope to stretch, absorbing the shock of the fall. The fall also jerks on the anchor components: the anchor point, the webbing, biners and pieces that are part of the anchor. If the anchor is not properly set up, the fall can cause parts of the system to fail.

The term static is also used to refer to rope and webbing that does not stretch or stretches very little; e.g., most webbing is considered to have up to two percent stretch. Dynamic rope is used as climbing rope to absorb the energy created in a fall. Static rope should never be used for actual climbing, although a hybrid between the two is useful for short climbs, such as in gyms.

The **direction of force** in a fall is usually straight down as dictated by gravity. In an anchor system set over the side of a cliff for climbing, the rope hangs from a single location, even if the anchor is suspended from two different trees, rocks, etc. For this rope, the direction of force is along the rope, usually straight down. When two (or more) forces act on an anchor, the forces can be combined into one resultant force.

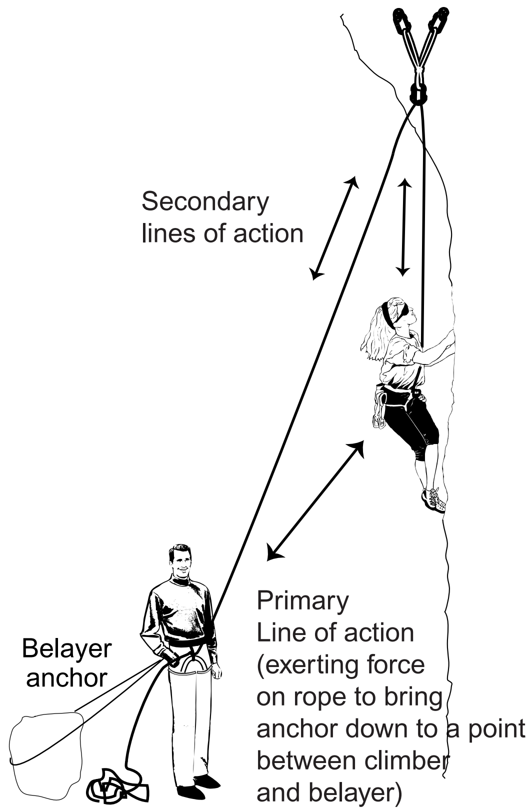
LINE OF ACTION

When a rope is pulled tight, it will align itself in a straight line, from the anchor to the pulling force (load). The rope will exert a force on any object in its path in an attempt to move it into the line of action. This pulling force (or load) is often the result of gravity, creating a vertical line of action.

In a slingshot anchor, the rope runs from the belayer (anchor) up through at least two carabiners and back down to the climber. The line of action is from the belayer to the climber, resulting in the rope exerting a force on the slingshot anchor when it tries to straighten itself into the line of action between the belayer and climber (fig. 14-01a). There are also two secondary lines of action running from the belayer to the anchor and the anchor to the climber.

In a simple top belay, where the climber is ascending straight up to the belayer, the line of action runs from the belayer straight down to the ground (fig. 14-01b). If the climber falls, the line of action does not change; it still runs from the belayer to the ground, right through the climber. Since there is nothing interfering with the line of action, the rope will not exert a force on any other object.

In a top belay involving a pendulum, where the climber is ascending at an angle to the belayer, the line of action

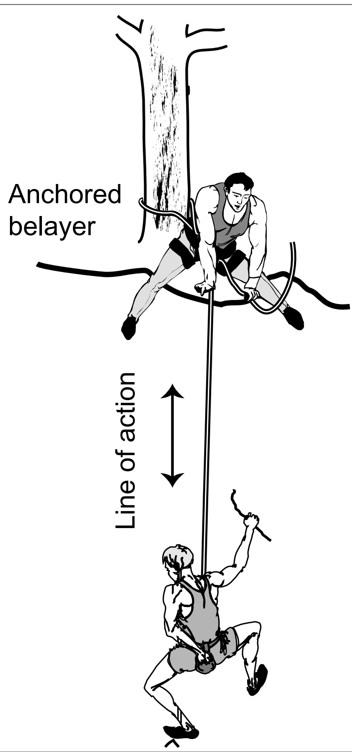


14-01a

14-01a–In a slingshot anchor, the rope-bearing biners (master point) attempt to move to a position directly between the climber and the belayer.

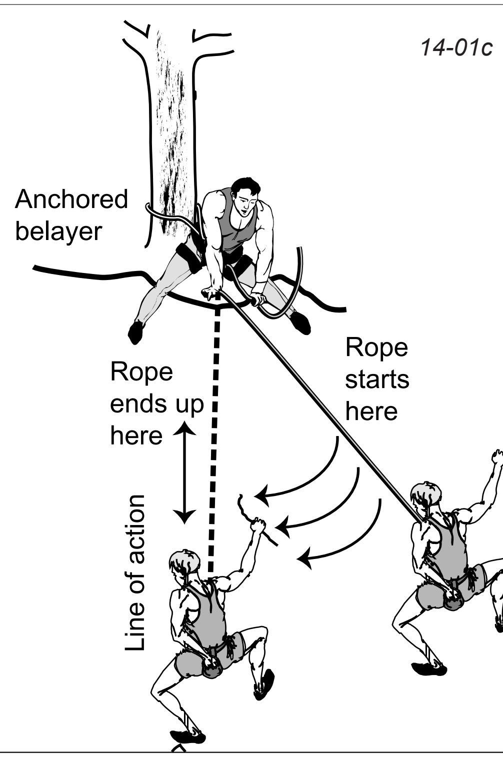
14-01b–In a standard toprope belay, the line of action is straight down to the climber.

14-01c–When a pendulum is involved, the load (climber) will immediately swing to the line of action



14-01b

14-01c



still runs from the belayer straight down (fig. 14-01c). If the climber falls, the rope seeks the line of action, causing the climber to swing to one side instead of falling straight down. Momentum carries the climber past the line of action, and the rope again seeks the line of action, reversing the swing of the climber. This happens until the climber's rope settles into the line of action or some immovable object (such as a slab of rock or the climber gaining a handhold) has stopped the rope from further moving into the line of action.

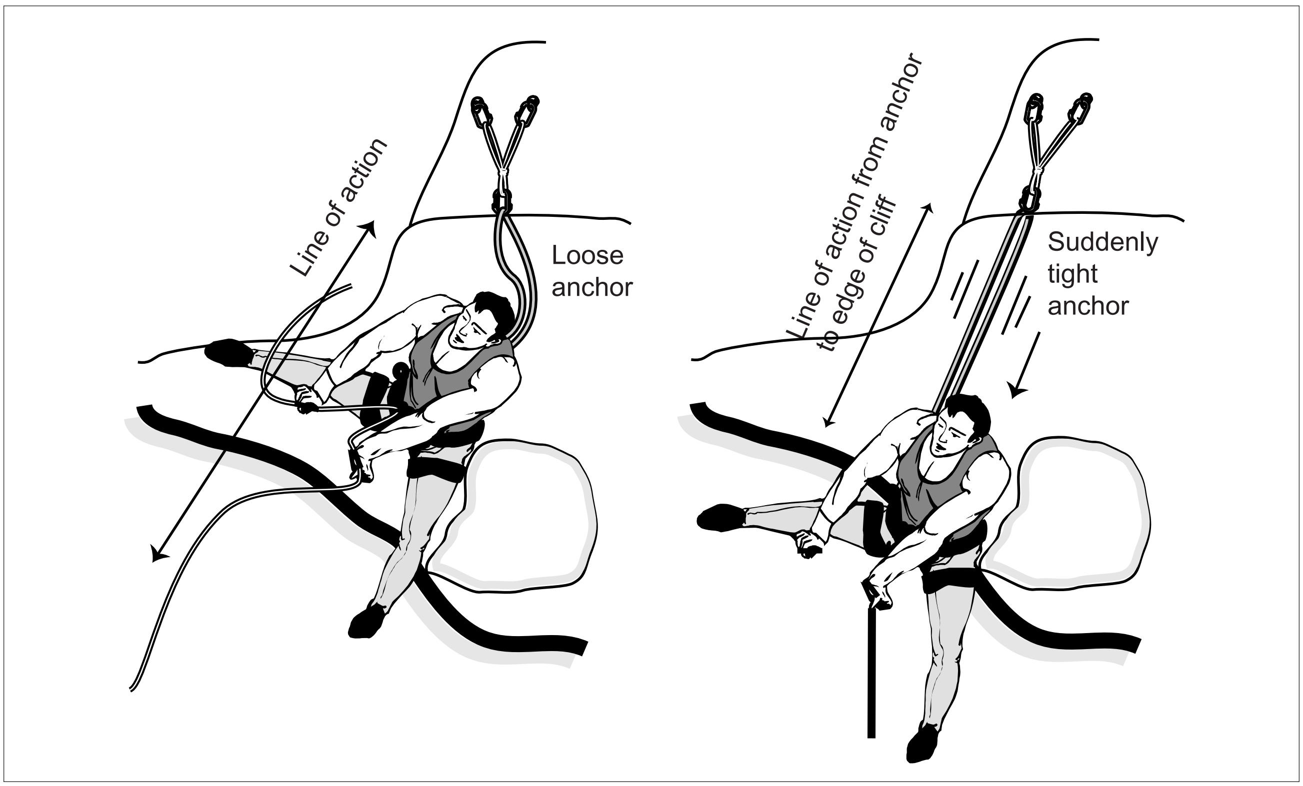
In a top belay where the belayer is sitting on a ledge but away from the edge with the anchor set behind and above belayer, the force from a fall will act to pull the belayer into the air (fig. 14-01d).

In a top belay where the belayer is standing on a ledge with the anchor set behind and below the belayer, the force from a fall will act to pull the belayer to his knees.

In a lead fall where the belayer is on a ledge below the leader and the leader has not yet placed a piece of protection, the belayer/anchor must be ready for a DOWNWARD pull. After placement of the first piece the force on the belayer from a fall will be UPWARD.

There are several dangers to the climber, the belayer, the rope and the anchor system when there is a sudden shift movement toward the line of action. The climber can get hurt by banging into a wall on a pendulum. The belayer can get hurt by being pulled to the side, to the knees, into the air, into the cliff, or in other directions, or by capsizing, rotating or twisting. The rope, while seeking the line of action, can run across sharp edges and cut instantly, as can webbing and rope components of the anchor system. Carabiners can be side-loaded and pieces can be pulled in directions they were not intended to resist.

It is important to anticipate where the line of action is in any normal climbing activity and where the force may take the belayer, climber, rope and anchor in the event of any kind of fall. By anticipating, you can take safety precautions such as directionals, or proper placement of anchor points.



14-01d–In a seated top anchor, it is best to position your belay stance right at the edge, often with legs dangling over. Doing so puts you directly in the line of action.

LEVERAGE

Leverage is "the mechanical advantage gained by use of a lever," like a crowbar. Leverage multiplies the force acting on an anchor component. We usually don't want the force multiplied. In the world of climbing anchors, a lever can be a tree, a rock or some hardware. It is generally important to wrap a rope or sling low to the ground on this lever to minimize leverage.

The higher on a tree a sling (or rope) is wrapped around, the more leverage the sling exerts on the tree (fig. 14-02a). It is much easier to "lever" the tree right out of the ground by wrapping it high and pulling sideways on it; if the tree is wrapped near the bottom, it becomes very difficult to "lever" the tree out. The same goes for branches; wrap branches near the junction with the tree trunk, not out on the end of the branch.

Boulders experience leverage the same way. If you want to roll a boulder, you exert pressure on the upper part, not down close to the ground; conversely, if you don't want it to roll, you exert pressure close to the ground. Wrap an anchor sling around a boulder as low as you can, rather than leaving the sling high on the rock. Also, when someone stands on the edge of a boulder rather than on the center, it tips over or rolls more easily. This becomes critical when the rock can be rolled, or "levered" toward and over the edge of a cliff. Be careful of wrapping a boulder so low that the sling becomes jammed underneath the boulder, or is pulled over sharp edges underneath. Not only can the sling become damaged or difficult (sometimes impossible) to remove, the boulder can roll and cut the sling, failing the anchor.

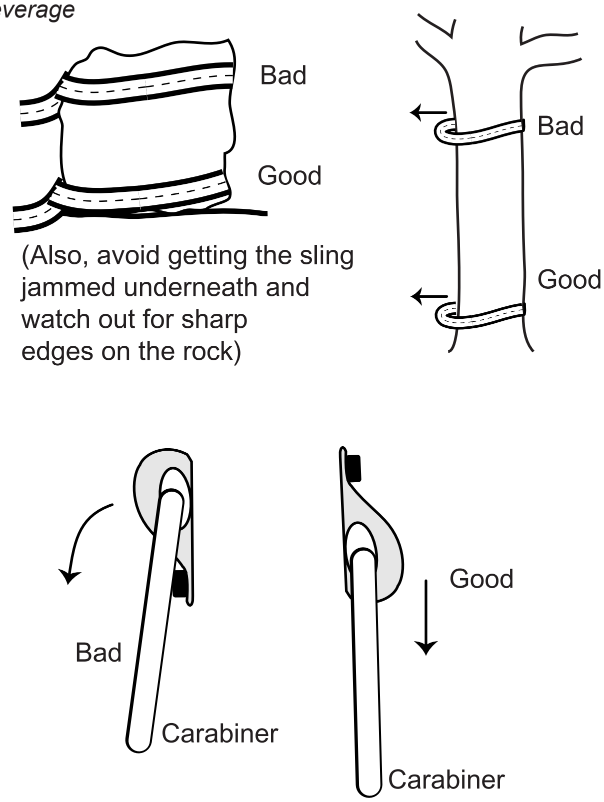
Bolt hangers are designed to be used in a certain direction. By misaligning them, you can exert leverage in the wrong direction, and it is possible to lever the bolt out of the rock. Always align bolt hangers in the proper direction to avoid this.

TORQUE

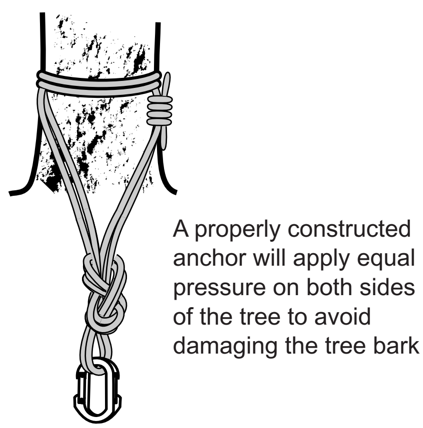
Torque is a rotational or twisting force instead of a linear force, such as in leverage. A child's top spins because torque is applied; drills use torque to bore holes.

In a properly constructed anchor around a tree, the coils of rope should exert equal force on the tree; unequal force will apply torque to one specific area of the bark and damage it (fig. 14-02b). A sling girth-hitched around a tree can exert torque on the tree depending on where the hitch is centered. If it is not centered in the direction of the load, the sling exerts torque on the tree and can damage the bark (fig. 14-02c).

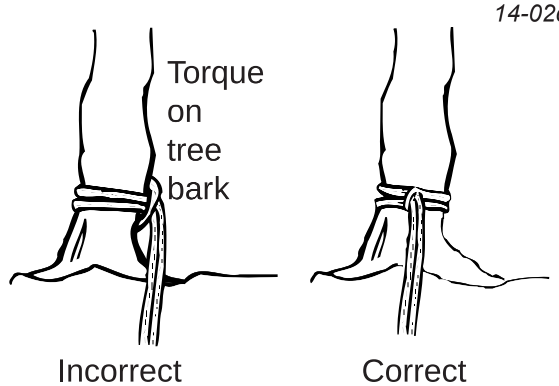
14-02a—Examples of good and bad leverage



14-02b



14-02c



FRICTION

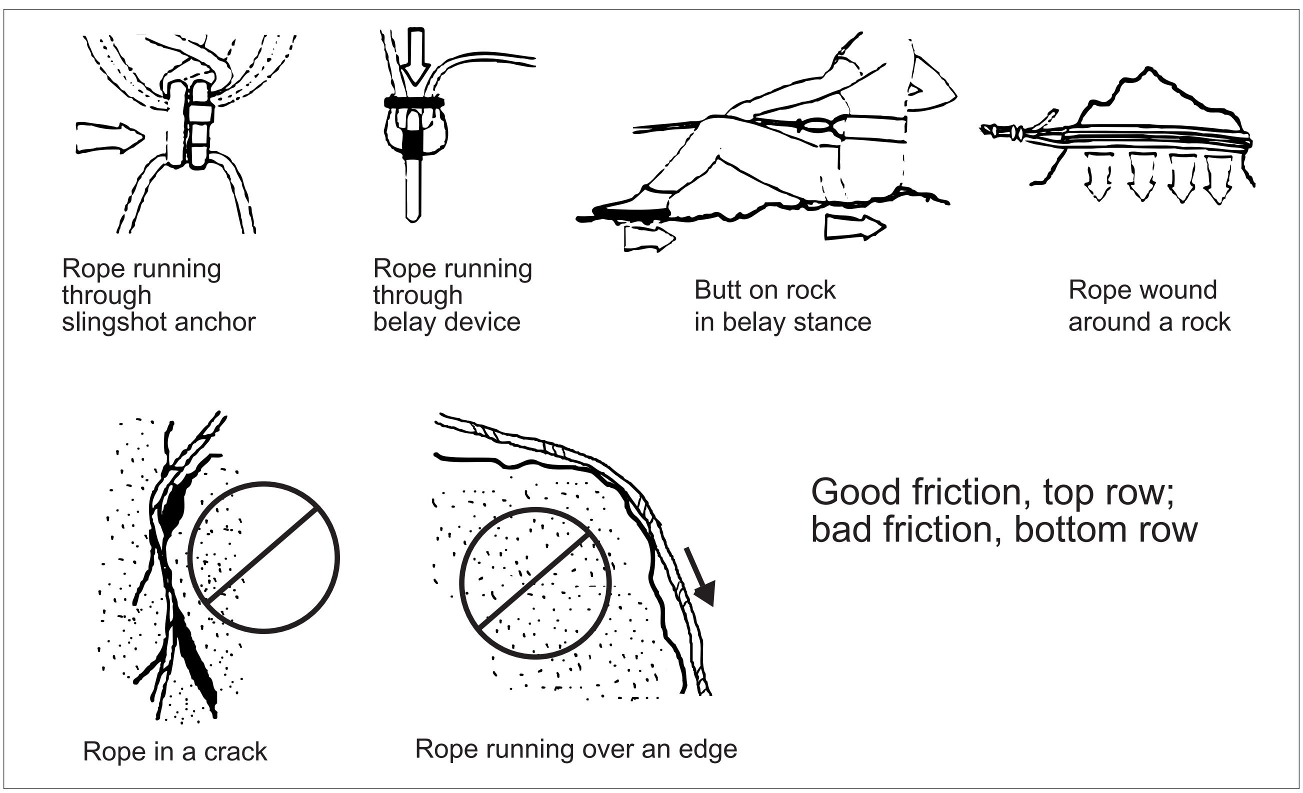
Friction is the surface resistance to motion; friction absorbs the energy required to continue or start motion, thus slowing it down or preventing it. Too much friction dissipates the absorbed energy by generating heat. In climbing situations, friction can be either good or bad.

Good friction is used in your belay device to stop a fall. The belay/rappel device (whether a slot-type ATC or Sheriff, a plate-type Sticht plate, or a figure-8 descending ring) is a variable friction device. The position of the brake hand controls the amount of friction the belay device exerts on the rope. By locking off the rope in your belay device, you apply enough friction to prevent motion. By adding friction to or subtracting friction from your rappel device, you can regulate the rate of descent when rappelling. If you need to slow down, you wrap the rope around your butt and add friction. To speed up again, you unwrap the rope.

When you sit down on a belay stance, your butt adds good friction to the belay system (fig. 14-03). The extra friction requires the falling climber to drag you across the rock to continue falling; since this is unlikely, the extra friction may make a safer belay. In general, the larger the surface contact area, the more friction is generated. Knots and hitches rely on good friction to keep from untying or moving. You use friction to “smear” on rock when you climb, both with your shoes and by using the surface area on your hands. The carabiners that hold the climbing rope in a slingshot anchor generate friction which helps the belayer to catch a fall; if a “frictionless” pulley were used in a slingshot_anchor, it would make it harder to stop a fall.

Bad friction can be dangerous. Too much friction generates heat, whether because of speed (rubbing too fast), contact area (rubbing too much of an area), or pressure (rubbing too hard). The excessive heat can burn nylon-based products like rope and sling. Rope running through a stationary sling will burn and fail the sling. A fast rappel generates heat in the metal rappel device, which can burn flesh or damage nylon rope.

Another danger of too much friction is that it can absorb all or part of the motion of the rope, causing it to drag or jam. A lead rope zig-zagging back and forth between pro placements builds up so much friction that the lead climber has difficulty standing and moving up. Rope running over edges or caught in cracks can damage the rope.



14-03

SHOCK LOADING

If a 180-pound climber stands on a bathroom scale, the scale registers 180 pounds. If the 180-pound climber jumps up in the air and lands on the scale, it registers a much higher weight, depending on how high the climber jumps. The higher the elevation to which the climber jumps, the greater the shock load at the end of his fall. This extra weight, or force, that is registered by the scale, is called a shock load, also known as an impact force or impact load.

You can stand on an aluminum soft drink can to smash it for recycling, or you can jump on it, which is easier because of the greater shock load. The farther you fall when climbing, the greater the shock load on the rope and anchor system. This shock load gets a lot worse in a lead fall than a top-rope situation.

As a general rule, you should avoid shock-loading your anchor. All anchors are more likely to fail if shock-loaded, even though a properly constructed anchor will be able to withstand most shock-loading. The shock load stresses the anchor components, accelerating the wear and tear that will force gear retirement.

To minimize shock-loading in an anchor, make the belayer part of the anchor system. The belayer's harness and body deformation will act to absorb energy. Use a good belay stance—well braced, with your butt on the rock. Eliminate the slack between the belayer and the anchor. Frequently the belayer can absorb all shock loading before it hits the anchor. The exception to this is when the climber outweighs the belayer by enough that it becomes dangerous for the belayer to absorb the shock. For example, a 100 pound belayer handling a 200 pound climber may want to belay the climber directly from the anchor to avoid bodily damage.

Also, help minimize shock loading on individual anchor components by spreading the impact force, or "equalizing" the anchor among two or more anchor points.

Dynamic ropes are used for climbing to absorb the shock load that occurs during a fall. The government tested parachute equipment during World War II and determined that a soldier could absorb about 2700 pounds of force, or shock load, before sustaining bodily damage. This research has been adopted as a standard by the climbing community (UIAA and CEN industry standards) for rope construction. While standards require that a dynamic rope absorb enough of the shock load to limit the force on the climber to, most modern ropes actually limit the force on the climber to 1800 pounds of force or less. Carabiners, harnesses, and other equipment are designed under the assumption that a dynamic rope will thus limit the force. Most top-rope falls result in less than 1000 pounds of force. If a static rope was being used, all the shock load would be passed on to the climber and equipment, with potentially fatal results.

The friction in the carabiners of a slingshot anchor absorb some of the shock load, allowing the belayer to stop a fall with less effort than the actual force of the falling climber.

The shock load can be manipulated in the belay system depending on the device and technique used. For example, a figure-8 descending ring used as a belay device will allow more rope to "run" through the belay before coming to a stop, thus absorbing shock load. A Petzl Gri-Gri will lock off immediately, passing on more shock load to the climber. A Muenter hitch belay locks off faster when the brake rope is pulled in the same direction as the load rope, but loses about 25% of its stopping power when the brake rope is pulled in the opposite direction. A slingshot or lead belayer who is not anchored can absorb shock by being pulled upward more than a belayer who is tightly anchored can (however, this increases the possibility of a loss of control of the belay). Some climbers consciously choose these belay devices or techniques to minimize shock load, but at the risk of other dangers.

Another source of shock loading is jumping while rappelling. Sport rappelling, or the military/police style rappelling, has its place, but that place is not on climbing anchors. Jumping, or shock loading, will over-stress the anchors. Use static rope and non-climbing areas to practice sport rappelling.

MULTIPLICATION OF FORCES

The multiplication of forces, or the increased force on anchor components due to excessive angles in the system, is the least intuitive and obvious of the anchor principles, and is perhaps best explained by the illustrations. Let's look at an example.

Two climbers have set a slingshot anchor (fig. 14-04a). The 100-pound climber is on belay and climbing. The climber falls and comes to rest, waiting to get back on the rock. At this point, the climber is exerting 100 pounds of force on the anchor. Friction in the carabiners at the top is helping to hold the climber; this friction is referred to numerically as "the coefficient of friction," which is about .67 in a carabiner. This means that the belayer only needs to exert 67 pounds of force to hold the 100-pound climber. The total weight on the anchor is 200 pounds. In explaining this increase in weight on the anchor, we say that the force on the anchor is "multiplied." (If the climbers had used a frictionless pulley instead of carabiners, the belayer would have to exert 100 pounds to hold the climber, as the coefficient of friction becomes 1.0. The total weight on the anchor would be 200 pounds. The friction in the carabiner is "good friction," because it puts less stress on the belayer.

Another example: Two slings have been girth-hitched around the same tree and run over the edge (two-point equalization). Two carabiners (reversed and opposed), connect the climbing rope to these slings. There is a zero degree angle between the two slings (fig. 14-04b). The load a 180-pound climber exerts on each sling is 90 pounds. Another way of saying this is to say that each sling is holding half the weight of the load (the climber).

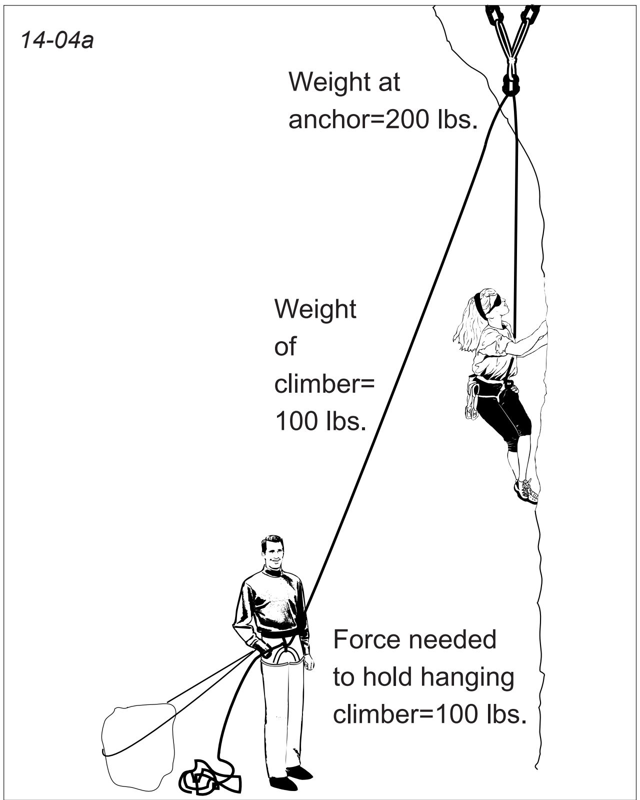
Multiplication of forces occurs when the angle between the two slings increases (fig. 14-04b). For example, if each sling is girth-hitched around a separate tree, with a resulting angle of 40 degrees between the two, the load on each sling becomes about 95.8 pounds—5.8 pounds more than the actual "half of the climber's weight." This occurs because there is not just a downward force (gravity) acting on each sling anymore. There is also a horizontal force pulling each sling toward the "center" of the anchor. The combination of these two forces—one vertical and one horizontal—results in the "multiplication of forces."

This multiplication increases as the angle increases, until at an angle of 120 degrees, the load on both slings is doubled—that is, the 180-pound climber is now exerting 360 pounds on the anchor, with each sling holding 180 pounds. When the angle increases even more, each sling holds more than the climber actually weighs. When the angle reaches 176 degrees (where the two slings are almost horizontal), one of the slings will break, with over 5100 pounds of force being exerted by the 180-pound climber (fig. 14-04c).

This leads to a general rule for setting an anchor: Always keep the angle between the slings connecting the two anchor points to the rope at less than 90 degrees.

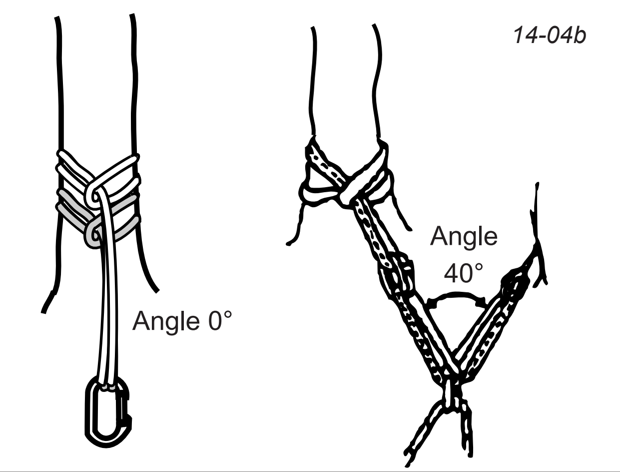
Why 90 degrees? At 90 degrees there is a multiplication of forces of roughly 45-50%. This means that each sling in

14-04a



14-04a–The 100 pounds of force needed to hold the climber consists of about 67 pounds of pulling force by the belayer and about 33 pounds of force in friction at the anchor biner.

14-04b



Multiplication of Forces
on Anchor Ropes and Slings
(Assuming a 180-pound climber hanging motionless from a two-point anchor)

The tension (load) shown is what each anchor point experiences.

Central angle	Induced tension
0	90
40	96
60	104
100	140
120	180
140	263
160	518
170	1033
174	1720
177	3438
178	5157 (rope and webbing break)
180	infinite

14-04c

the example above is holding about 120 pounds. We consider this “acceptable.” Our anchor components should safely hold far more than this. And we could increase the angle safely; the 120-degree angle results in 180 pounds on each sling and the sling is rated at over 4500 pounds. We choose 90 degrees because it is easy to visualize without any special equipment. It is a right angle, or a square corner.

Another reason to use 90 degrees or less is to consider the consequences if one sling should fail. The smaller the angle, the less the distance the remaining anchor components can swing, over sharp edges or whatever else may be in the way, seeking a new line of action.

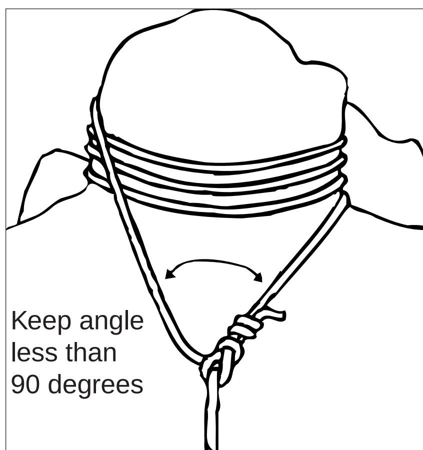
This rule applies to other situations as well. It applies to the angles formed by runners around a boulder or the coils in a bowline-on-a-coil, girth hitch or candy stripe bowline (fig. 14-04d). In equalization configurations that have more than two slings (such as three-point equalization), watch out for the outer two slings on the setup—the angles of the inner slings may be good but the other slings may exceed the desirable limits.

If the anchor points you are using are too far apart, reduce the angles by using longer runners or selecting anchor points closer together.

Another technique is commonly used when setting anchors. It has been referred to in some literature as the “American triangle” (fig. 14-04e). This occurs when a single sling is threaded through two anchor points such that the anchor points and the rope connection form a triangle. This is a configuration we avoid, because the forces multiply much faster than in the standard two-point equalized setup in the first two examples.

In the previous example, the forces doubled at 120 degrees. When using an American triangle, the forces double at 60 degrees.

If you have an anchor with two slings girth-hitched around two trees right next to one another, resulting in a five-degree angle between the two slings, an American triangle is perfectly safe to use. The problem comes at greater angles. In order to prevent any problems, simply eliminate it as an option; then you needn’t worry about what the maximum safe angle is.



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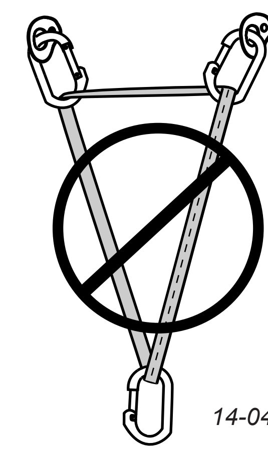

14-04e

The "American triangle" is considered unsafe

SUMMARY OF RECOMMENDATIONS

- As a belayer, always try to be in the line of action.
- Determine the direction of force and set up the anchor in that direction.
- Orient pieces (like cams) toward the direction of force.
- Avoid levering out your anchor—place ropes low on trees and boulders.
- Avoid shock loading anchors.
- Limit the angle between the outermost slings in an anchor to 90 degrees or less.
- Limit “American triangles” to 60 degrees or less; better yet, don’t use them.
- When possible, inspect anchors set up by someone else; have your anchors inspected by others.
- When you climb to the top of a slingshot anchor system, make sure all anchor components are still intact. Ensure any lockers are still locked, they are oriented in the proper direction, etc.
- We’ve only given you principles of anchors; these are basic guidelines you can use. As in so many things you will not be able to satisfy all principles simultaneously; you will have to make tradeoffs. There is no substitute for good judgment. Use your head and think!