






Physics of Rock Climbing: Anchor Lab

Lab purposes: The Physics: To understand the vector nature of force.
 The Climbing: To understand how force bears on climbing anchors.
 The Experience: To use the physics understanding of the vector nature of force to design climbing anchors according to the style and needs of the climber.

Motivation: In the roped climbing game, climbers must periodically construct belay anchors whose integrity must be impeccable. Belay anchors are typically made with several individual anchoring devices, in part because redundancy is needed for impeccable integrity and in part because the strength of a single anchor may not be sufficient to withstand the most severe loads that might be expected (~20 kN). The individual anchor devices are then connected together with carabiners and webbing to complete the anchor. Figures 1a through 1e show the construction of a belay anchor. Figure 1a shows the rock at the belay stance; Figure 1b shows the anchor devices in place. Figure 1c shows the anchor devices connected together with a sling, and Figures 1d and 1e show the resulting anchor weighted by a climber. Construction of such an anchor requires an understanding of the limitations of the individual components and an understanding of how to combine the components. One fundamental aspect of the combination is an understanding of how the force applied by the climber is transmitted to the individual anchors. This lab teaches the vector analysis needed to add forces.

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| <p>Figure 1a A view of a typical belay stance. The climber must decide where to place anchor devices.</p> | <p>Figure 1b Anchor devices in place.</p> | |
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| <p>Figure 1c The rigged anchor: the anchor devices are connected by webbing.</p> | <p>Figure 1d The weighted anchor: the magnitudes of the forces on each anchor point are about equal.</p> | <p>Figure 1e The climber anchored at the belay stance.</p> |

Forces as Vectors

A force is represented as a vector; it has both a magnitude and a direction. It can be depicted as an arrow; the arrow's length shows the magnitude of the force, and the arrow's orientation shows the direction of the force. A force or tension in a rope is transmitted along the rope's length. The importance of the directional quality of force is understood intuitively by climbers: when top roping a vertical climb, it can be reassuring if there is a little bit of tension in the rope, a small force pulling upwards (Figure 2a). When climbing through an overhang, or along a traverse, the extra tension in the rope is disconcerting because it pulls the climber off the rock (Figure 2b). When force is expressed without the directional information, the direction is taken from context. For instance, one might say "I weigh 180 pounds," without needing to say that this force pulls down.

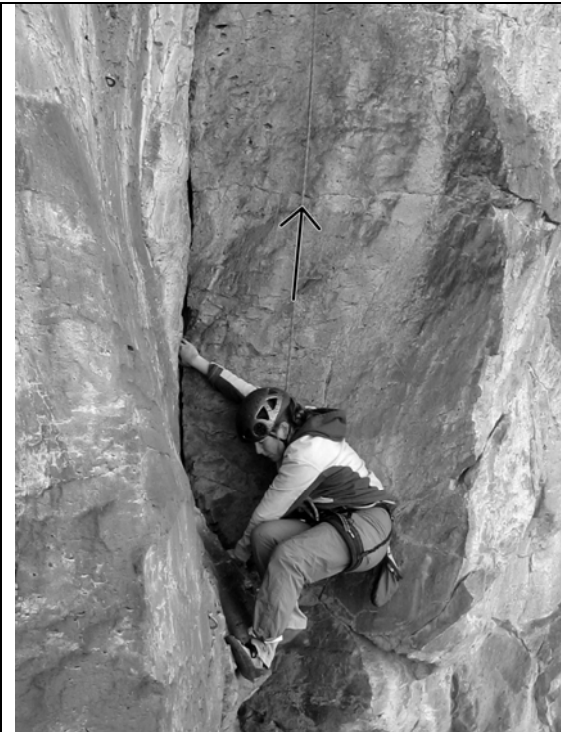


Figure 2a When the rope pulls up, it is generally reassuring. The arrow show the direction of the force exerted on the climber by the tension in the rope.

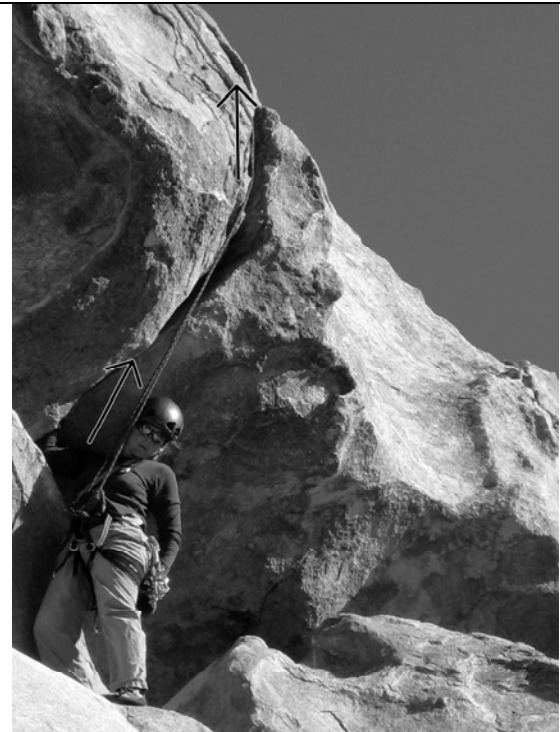


Figure 2b When the tension in the rope pulls the climber out away from the rock, it can precipitate an unnerving swing.

Adding Forces

Force addition takes both the magnitude and direction information into account. Graphically, force addition can be represented by placing the vectors head to tail; the orientation of the arrows must be maintained. If the vectors point in the same direction, the magnitudes can simply be added. If the vectors do not point in the same direction, then trigonometry must be invoked to calculate the sum. Several equivalent methods can be used according to whim, ease, or familiarity. Figure 3 shows examples of force addition in climbing situations.

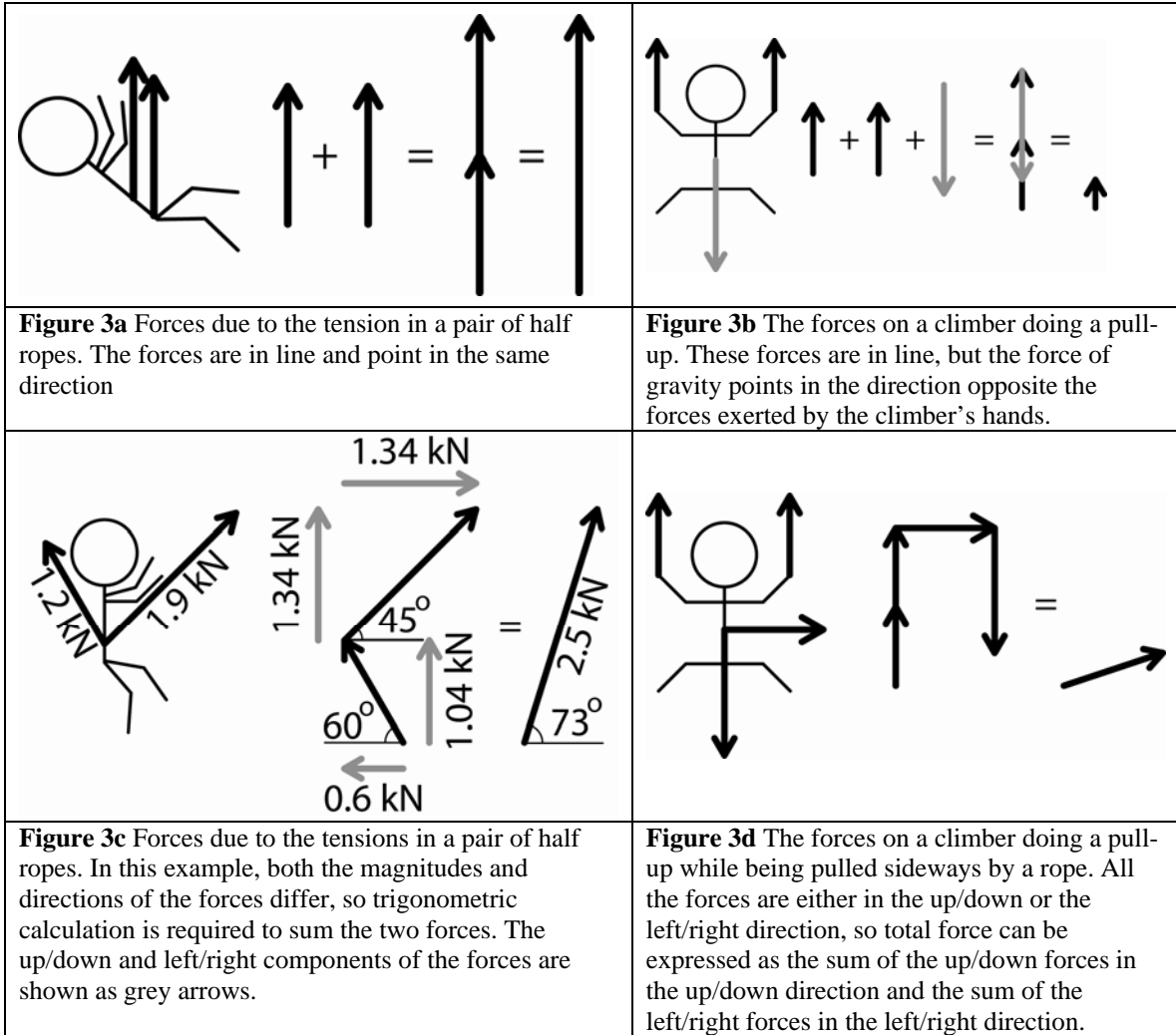


Figure 3a shows an example the forces that might be exerted on a climber due to tension in a pair of half ropes. (A climber might choose to climb with a pair of half ropes rather than with a single rope. A pair of half ropes has the advantage of redundancy and the disadvantage of extra weight.) Here, both the magnitudes and the directions of the tensions are identical; the resulting sum is twice as large and points in the same direction.

Figure 3b shows the forces on a climber doing a pull-up; two equal forces at the hands pull upwards, and gravity pulls down. (The gravity vector is shown in grey). Summing the vectors by placing them head to tail results in a net force whose magnitude is two times the force exerted by a single hand minus the force of gravity. The direction of the net force points up or down depending on whether the arms are pulling up

more than gravity pulls down. Here, the climber is pulling more than gravity and the net force is in the up direction.

Figure 3c shows another example of forces that might result from a pair of half ropes. In this situation, the tensions in the ropes differ in both magnitude and direction. Placing the two force vectors head to toe provides a graphical representation of the sum of forces due to the ropes. Trigonometry is needed to numerically calculate the magnitude and direction of the sum. Different strategies can be used to arrive at the sum. One approach is to use the law of cosines to find the length and angle of the sum; in this example: $L_{length} = 1.2^2 + 1.9^2 - (2 \times 1.2 \times 1.9 \times \cos(105^\circ)) = 2.5$ and $A_{angle} = 120^\circ - \arccos((1.92 - 1.22 - 2.52) / (-2 \times 1.2 \times 2.5)) = 73^\circ$. A second approach is to componentize the vectors and add the components. The left/right component of the 1.2 kN force is 0.6 kN ($1.2 \times \cos 60^\circ$) pointing to the left; the up/down component is 1.04 kN ($1.2 \times \sin 60^\circ$) in the up direction. The magnitudes of both the left/right component and the up/down of the 1.9 kN force are 1.34 kN ($1.9 \times \cos 45^\circ$ and $1.9 \times \sin 45^\circ$), pointing right and up respectively. The sum of the forces is a vector whose components are 1.34 kN minus 0.6 kN, 0.74 kN to the right and 1.34 kN up plus 1.04 kN up, 2.38 kN up. The angle is the $\arctan(2.38/0.74)$, 73° .

Figure 3d shows all the forces on a climber doing a pull-up and being pulled sideways by a rope. In this example, the forces are already componentized, so the sum of the forces can be found by adding the forces in the up/down direction (twice the force exerted by each hand minus the force of gravity) to get the total force in the up/down direction and by adding the forces in the left/right direction—only the force due to the tension in the rope—to get the total force in the right/left direction.

Estimating the Force on an Anchor Device

Successful anchors keep climbers stationary, a situation that lends itself to an analysis using Newton's 2nd and 3rd laws: *force is equal to mass times acceleration ($F=ma$)* and *for every action there is an equal and opposite reaction*. This class of problems is often referred to as statics. Solutions are derived by setting the sum of all the forces on an object to zero. This net force must be zero for the object to remain static; if the net force is not zero, the object accelerates. One statics problem that confronts climbers is the estimation of the force on an anchor device.

Figure 4 shows a way to determine the forces on the anchor devices in the anchor set-up depicted in Figure 1. Figure 4a shows the directions of the different forces, which are in line with the tensioned webbing. Given the angles at which the forces act and the presumption that the magnitudes of the forces on the anchor devices are equal, the three anchor device forces are added by placing them head to tail; the sum must be equal and opposite to the force on the climber. The result is that the magnitude of the force on each anchor is 1/2.64 (0.38) the force on the climber. This result does not differ much from the expectation that with three anchor devices, the force on each would be 1/3 of the total. In this example, each anchor device is capable of sustaining a load of 12 kN, so the maximum load the anchor can sustain is about 31.5 kN, significantly more than the maximum force climbers can generate even in a worst case scenario.

The force on an anchor device rises swiftly as the angles become more obtuse. Figure 5 shows such a situation, which can be recognized by the "wide Y" formed by the anchor webbing. In this example, the force on each anchor device is nearly double that of the force on the climber. If each anchor device is capable of sustaining a load of 12 kN, the maximum load the anchor can sustain is only 6 kN, a fraction of the expected load.

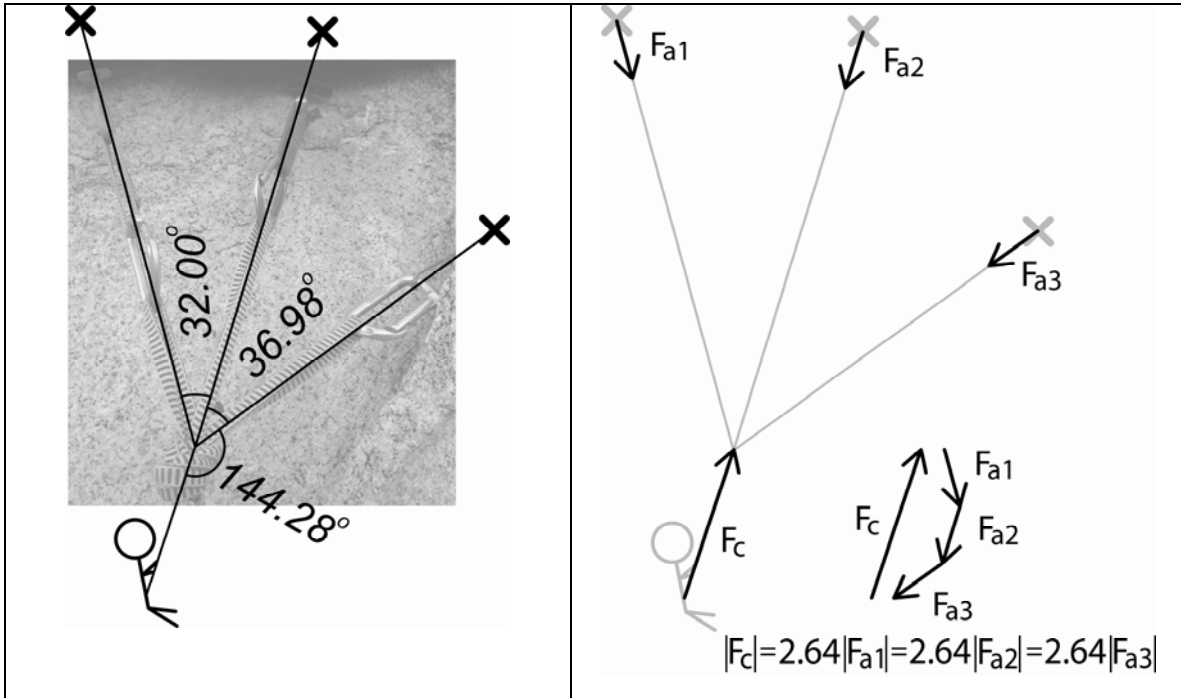


Figure 4a Diagram of the angles at which the forces in Figure 1d act. The forces act in line with the webbing and converge at the knot. For the knot to remain stationary, the net force exerted on the knot must be zero; conversely, the force exerted on the climber must be equal and opposite to sum of the forces on the anchor devices.

Figure 4b The force exerted by the climber is equal and opposite to the force exerted by the anchors. Laid head to tail, the anchor force vectors sum to the force exerted on the climber. Presuming the anchor is equalized, the magnitude of the force on the climber in this situation is about 2.64 times the magnitude of the force on each anchor device.

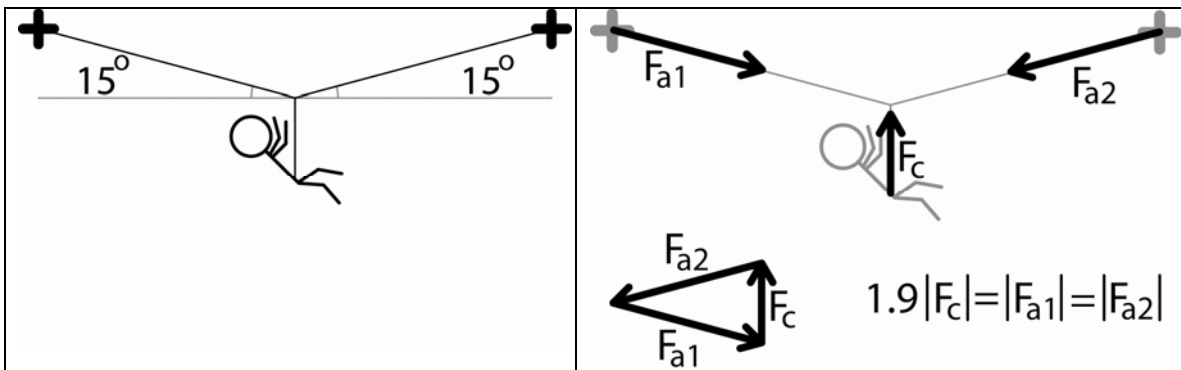
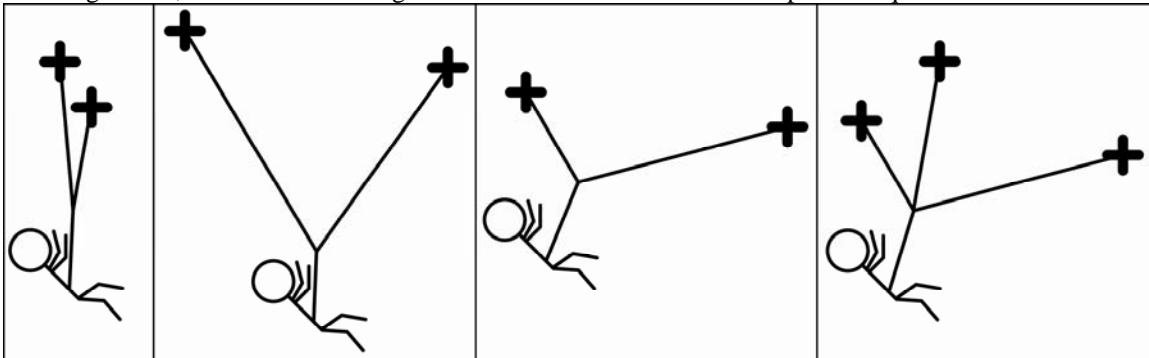


Figure 5a An example of an anchor with a “wide Y” that results in high forces on each anchor device.

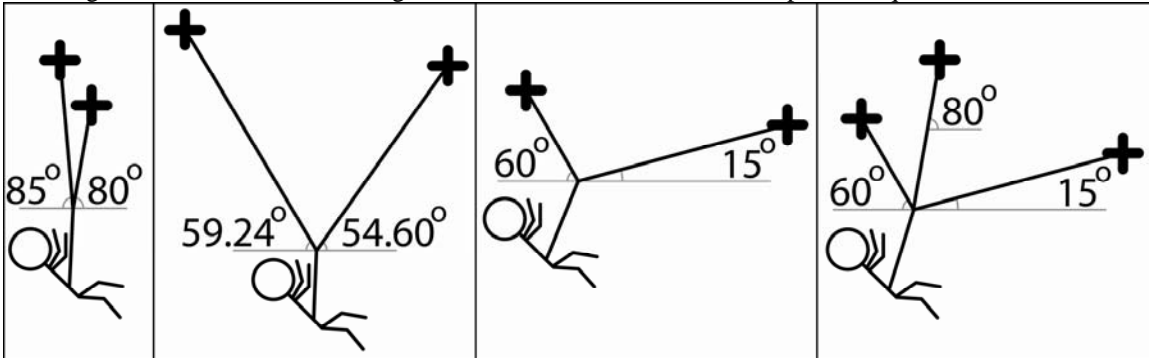
Figure 5b Each anchor must sustain about twice the force applied by the climber. For many anchoring devices, this anchor would not sustain the forces that might be applied.

Exercises

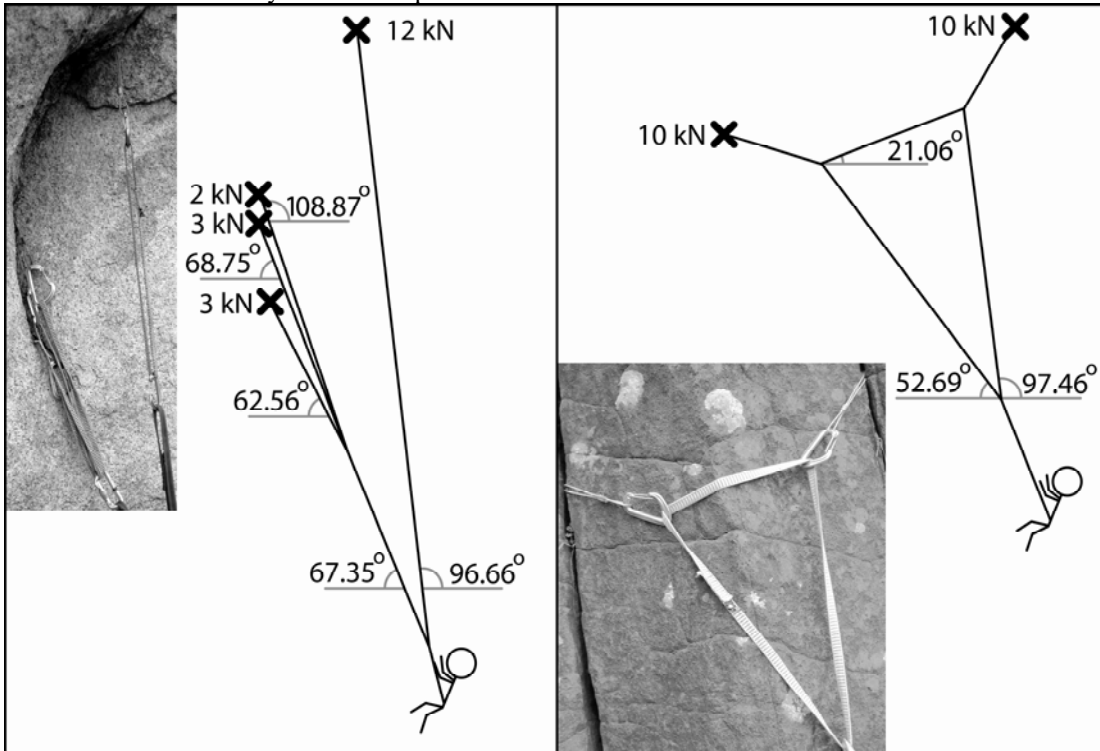
1) Estimate the ratio of the magnitude of the force on the climber to the magnitude of the force on each anchor device. For each configuration, assume that the magnitude of the forces on each anchor point is equal.



2) Calculate the ratio of the magnitude of the force on the climber to the magnitude of the force on each anchor device. For each configuration, assume that the magnitude of the forces on each anchor point is equal.



3) For the configurations shown below, determine the maximum force that the climber can apply to the anchor. In what direction does the force exerted by the climber point?



Lab, Part I

Venue: Can be done in the classroom or at the cliff. Perhaps best to do this part in the classroom as variables may be easier to isolate.

Equipment: Anchor points; force measurement devices (tension, e.g. fish scale or load cell), at least 2, 3 or 4 would be best; a weight or two, commensurate with the forces measurable by the scales, best not to use actual students without plenty of supervision; sling, cord, or rope, again commensurate with weights and scales. A poor man's version might be possible with paper clips, rubber bands, pennies (weights) and string.

Objective: Develop an ability to estimate the forces on anchor devices.

Deliverables:

- Identify good, bad, and in between anchor configurations
- Construct an equalized anchor, given anchor points
- Estimate maximum anchor load, given anchor device strengths

Activity: Construct different anchor configurations and measure the resulting forces

Anchor Design

Force considerations are only one factor that must be addressed in anchor construction. In general, several qualities are desirable in an anchor. The word on the street is that anchors must be “SERENE”: Solid, Equalized, Redundant, and Non-Extensible. Further the anchors should be constructible in a timely fashion, should be simple enough that their integrity is easy to see by inspection, and should be able to sustain loading in all likely directions. These seven desirable qualities are rarely all satisfied by a single anchor configuration. Instead, the climber must make design tradeoffs. To do so requires an understanding of what should be maximized, a quality that each climber must determine according to his/her inclinations and the particular situation. For example, climbers in danger of being caught in a thunderstorm might opt to make anchors from fewer anchor devices to save time and thus reduce the danger of being struck by lightning. Or a climbing instructor teaching a group of novices might elect to construct an elaborate, time consuming anchor because anchor impeccability is of the highest concern when novices are climbing. Thus, the climber needs to choose what qualities to maximize and then design around these qualities.

One trade-off situation that is common when building an anchor is the choice between equalization, redundancy, and non-extension. The equalization scheme shown in Figures 6d-f permits extension in the event of the failure of a single anchor device. Further, the failure of the sling would result in catastrophic anchor failure. A simple remedy is to tie an overhand knot at the nexus as shown in Figures 6a-c; doing so greatly reduces the possible extension and creates two independent loop pairs—if the sling cuts in one place, the anchor is still viable. The disadvantage of the added knot is that it eliminates the equalization of forces if the force is not applied in the single, equalized direction (Figures 6a and 6c).

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| <p>Figure 6a The knot at the nexus reduces extension in the event of the failure of a single anchor device but removes the equalization of forces.</p> | <p>Figure 6b This anchor is both equalized and the extension is reduced by the knot. The slings are now redundant.</p> | <p>Figure 6c Again, the knot at the nexus reduces extension in the event of the failure of a single anchor device but removes the equalization of forces.</p> |
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| <p>Figure 6d The equalized sling is not redundant, and the extension is large in the event of anchor device failure.</p> | <p>Figure 6e The equalized sling maintains equal forces regardless of the direction of the force applied by the climber.</p> | <p>Figure 6f As the force revolves around the anchor, the nexus point traces the shape of an oval.</p> |

Lab, Part II

Venue: Best done at the cliff but can be done in the classroom.

Equipment: Anchor devices, webbing, carabiners. Force measurement devices might be a plus. If the exercise occurs in the classroom, Velcro attachments points, dental floss/cord, and paperclips.

Objective: Develop the ability to construct quality anchors.

Deliverables:

- The ability to reliably construct quality anchors
- The ability to estimate the maximum force an anchor can sustain.

Activity: Construct climbing anchors based on different situations. Can be turned into competitions for anchors that:

- Take the least time to build
- Sustain the highest force
- Are constructed using the fewest components