CNS Institute for Physics Teachers

Title:	**The Physics of Rock Climbing**
Version:	October 28, 2005
Authors:	Hallie Snowman, Jim Overhiser, Arthur Woll
Appropriate Level:	Regents Physics
Abstract:	When rock climbing, anchors are used to guide and support a rope attached to the climber. It is critical to set up anchors so that in the event of a fall, the forces generated on the anchor will not cause it to fail. Students design and optimize various anchor systems to support a "climber" represented by a 10 N weight.
Time Required:	Two 40-minute periods
NY Standards Met:	5.1b A vector may be resolved into perpendicular components. 5.1c The resultant of two or more vectors, acting at any angle, is determined by vector addition. 5.1j When the net force on a system is zero, the system is in equilibrium.
Special Notes:	**The Physics of Rock Climbing** is available as a kit from the CIPT Equipment Lending Library, www.cns.cornell.edu/cipt/.

Objectives:

- To investigate two-point anchor systems for a top-rope used in rock climbing.
- To practice free body diagrams and vector addition.
- To explore the relationship between magnitude and angle of forces exerted on object in equilibrium.

Class Time Required:
Two 40-minute periods

Teacher Preparation Time Required:
10 minutes

Special Equipment Per Group:

- Smooth wall, metal lockers or white board space for mounting suction cup anchors
- CIPT rock climbing kit (see teacher info section)

Materials Needed:

- meter stick
- 4' space on a smooth wall, whiteboards, or lockers
- 1 kg weight (put small sock on weight to prevent it from scratching surfaces)
- dry erase marker (optional)
- 1-2 small carabiners (not meant for climbing)
- 2-3 slings of rope (1/8" or larger braided rope cut into 18" lengths and tied into loops)
- 2-3 suction cups with hooks
- protractor (ideally with line level attached and 60°, 90° and 120° angles marked centered on vertical)
- 2-3 20 N spring scales

Materials Needed for Series vs. Parallel Forces Demo:

- 2 springs
- 2 10N spring scales
- string
- ringstand with clamp
- tape

Assumed Prior Knowledge of Students:
Graphical analysis, free body diagrams, vector addition.

Background information for Teachers:
See answers to questions in the student section below. Special thanks to Jean Amodeo, technical advisor/climbing buddy.

Answers to Questions:
Prelab:
Physics of Rock Climbing: Glossary

Terms: *More definitions of climbing jargon at* http://www.myoan.net/climbing/jargon.html

- Belay *A technique of controlling the rope to insure the climber doesn't fall very far. The rope feeds easily in one direction to allow the climber to ascend, but a simple change in direction of the brake hand increases frictional force, allowing the belayer to stop the rope with minimal effort force.*
- Lead climbing *Style of climbing in which the first climber (the leader) places protection as he/she climbs and is belayed from below*
- Top Rope Climbing *Climbing where an anchor system at the top guides the climbing rope. Belayer may belay from the top or the bottom of the climb.*
- Anchor *Any tree, block, nut, bolt, friend, cam or other protection device that holds a climber to a cliff with rope, slings and carabiners.*

Equipment:

- Carabiner *An aluminum, steel or titanium snap-link used for holding the rope and connecting it to gear. May be locking or nonlocking.*
- Sticky Rubber *Rubber with an extremely high coefficient of friction on rock.*
- Sling *Loop of nylon or Spectra/nylon, webbing or cord. Usually carried over one's shoulder -- single, doubled or tripled, depending on the length of the sling.*
- Hex *Short for Hexentric. A hollow, nut-like, hexagonal-shaped type of protection.*
- Tri-cam *A type of protection which rocks into a wider position when pulled.*
- Spring-loaded cam *A type of protection which uses springs which push out into a wider position when pulled.*

Anchor Systems I

Analysis Questions:

1. Examine the anchor systems you created for supporting the "climber" (the 10 N weight). How did the angle between the two anchors affect the forces on the anchors? *In general, as the angle between the anchors increases the tension (force) on the rope attached to the anchors increases.*

2. Examine the three anchor systems with a 90° angle. How did the forces on the anchors compare when the anchors were in different vertical positions? What is the cause of this relationship? *As the vertical distance between the two anchor points increased, the forces on the two anchors became more unequal. The higher anchor point had the greater force because the angle of the sling was in a more vertical*

direction and it counterbalanced more of the downward force of the weight of the "climber."

3. Anchor systems are safest when they equalize forces. Explain why and give examples. *Beyond some maximum force, an anchor point will fail. Having an anchor system that equalizes the forces on each anchor point avoids the situation that one of them is holding most of the weight and minimizes the danger that one of the points will fail.*

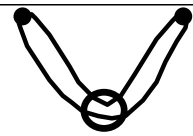
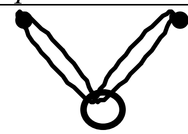
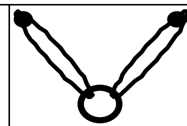
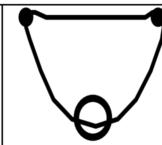
4. Though an average climber weighs about 600 N, a typical fall can exert a force of up to 12,000 N on the anchor system. What could account for this much larger force? *When the 600-N climber falls some distance, he or she acquires a downward velocity. Therefore, to stop the downward motion of the climber, the rope must exert a force ($F=ma$) that accelerates the climber in the upward direction in addition to supporting the weight of the climber. In climbing jargon, this is called "shock weight."*

5. From what you have learned in this lab, design an ideal anchor system that minimizes the forces on the anchors. Draw your system below. *Answers will vary. In general, the angle between the slings should be narrow and the anchor points should be level. The more anchors, the better.*

Extended task:
Using your newfound knowledge of anchors and top-rope climbing, use the ropes, suction cups, scales and carabiners to set-up a system which has three (3) rope anchors. Collect the data from your set-up and construct an equilibrium (head-to-tail) diagram on a piece of graph paper.
An equilibrium graph should show a closed design indicating that the forces are at $\sum F = 0$. The laws of motion dictate that if the climber is not moving then all forces must be balanced.

Anchor Systems II: The American Death Triangle

Answers are subjective, but here are the main points:

Anchor System anchors carabiners	 One sling untwisted	 One sling in figure eight with carabiner through each side of the figure eight	 Two separate slings	 American Death Triangle: One sling hooked in a triangle as shown
Sling Failure: Imagine what would happen to the climber if the sling broke at any point. You may manipulate the anchor system to test but do NOT cut the sling.	*Climber falls* -	*Climber falls* -	*Other sling saves climber* +	*Climber falls* -
Anchor Failure: Simulate anchor failure by unhooking one of the slings from the anchor. What happens to the climber? The other anchor?	*Carabiner slides off of sling and climber falls* -	*Climber does not fall* +	*Climber does not fall* +	*Climber does not fall* +
Forces on Each Anchor: Use spring scales to examine the forces on each of the anchors. Remember to adjust the anchors to keep the angle between the forces at a constant 60°.	*Less force on anchors* +	*Less force on anchors* +	*Less force on anchors* +	*More force on anchors* -
Are Forces Self Equalizing? Anchors are safest when weight is equally distributed. Move position of the climber back and forth. Are the forces equal on each side?	*Forces self equalizing* +	*Forces self equalizing* +	*Forces not self-equalizing. If slings pull unequally, one anchor may bear all the weight, increasing likelihood of failure* -	*Forces self equalizing* +
Shock Weighting During Anchor Failure: Using spring scales to measure forces, simulate anchor failure by unhooking one sling and dropping it. What happens to the climber? The force on the remaining anchor?	*Carabiner slides off of sling and limber falls* -	*Carabiner slides to end of sling, shock-weighting the other anchor,* -	*Other anchor is not shock-weighted* +	*Carabiner slides to end of sling, shock-weighting the other anchor* -
Rank subjective:	*Worst*	*Usually best*	*Good*	*Second worst*

Conclusion:
What did you consider to be the safest anchor system? Back up your choice according to each of the criteria listed above. *Good cases can be made for both middle arrangements. Anchor failure is much more likely than sling failure and is usually caused by high forces, unequalized forces, shock weighting or protection being incorrectly placed or pulled in an unanticipated direction. Interestingly, most falls in climbing are not due to anchor failure but happen when climbers rappel (slide down rope in a controlled fashion) off the end of their rope.*

Evaluation question:
Each of the anchor systems examined in the lab is designed to have a rope passed through the carabiner when climbing as shown in Figure 1. Figure 2 illustrates a simpler system that does not use a carabiner. What are the advantages and disadvantages of this carabiner-less anchor system? Explain your answer according to the criteria examined in this lab and any other criteria you might think of.

Figure 1

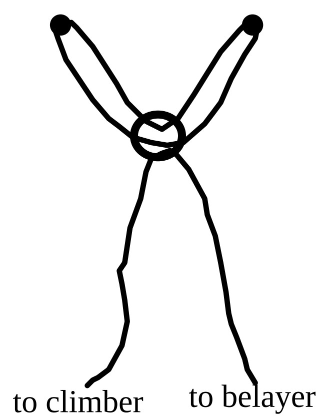
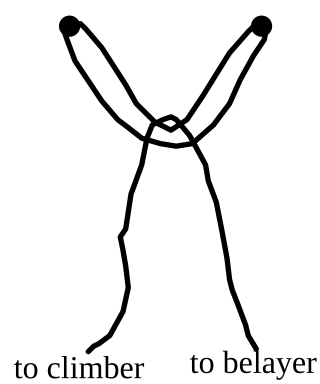


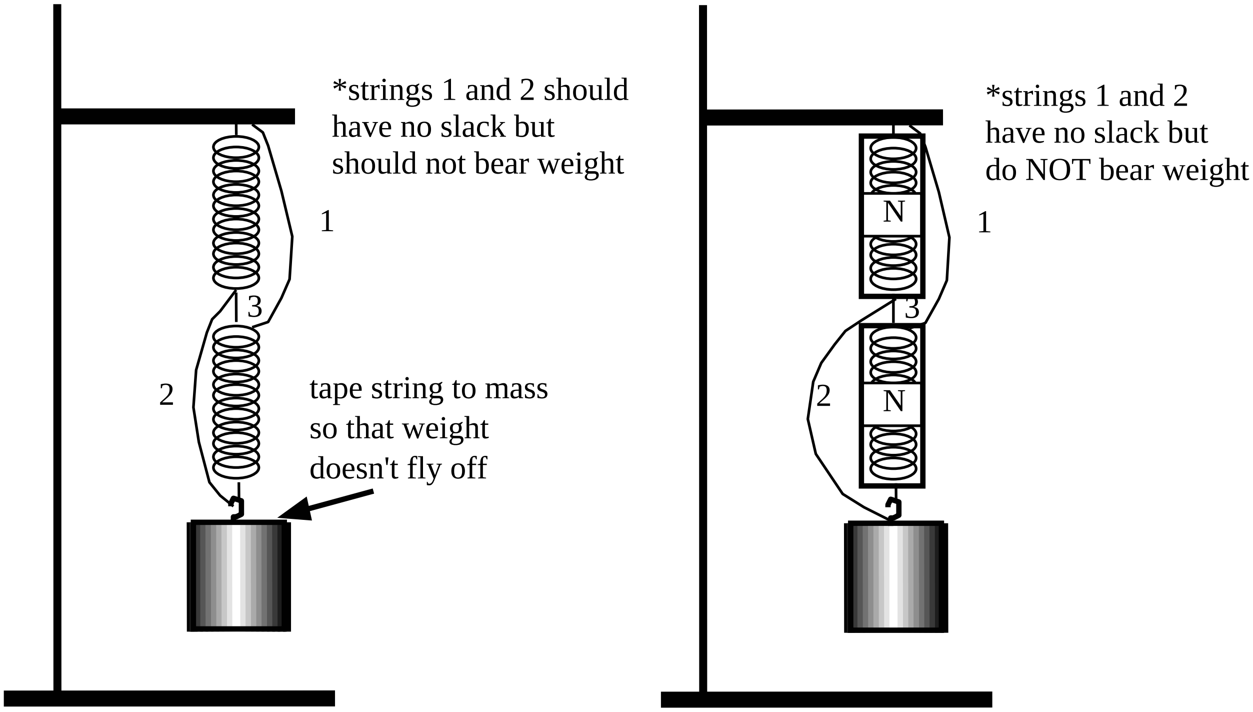
Figure 2



In general, it is better to have fewer links in the chain of protection, so at first glance, Figure 2 seems safer since it doesn't depend on the carabiner in addition to the sling and rope. However, the friction in Figure 2 would be much higher. So high, in fact, that the heat of friction could melt the nylon rope and webbing and lead to catastrophic failure.

Tips for Teachers:
(The notes in this section closely follow the student instructions.)

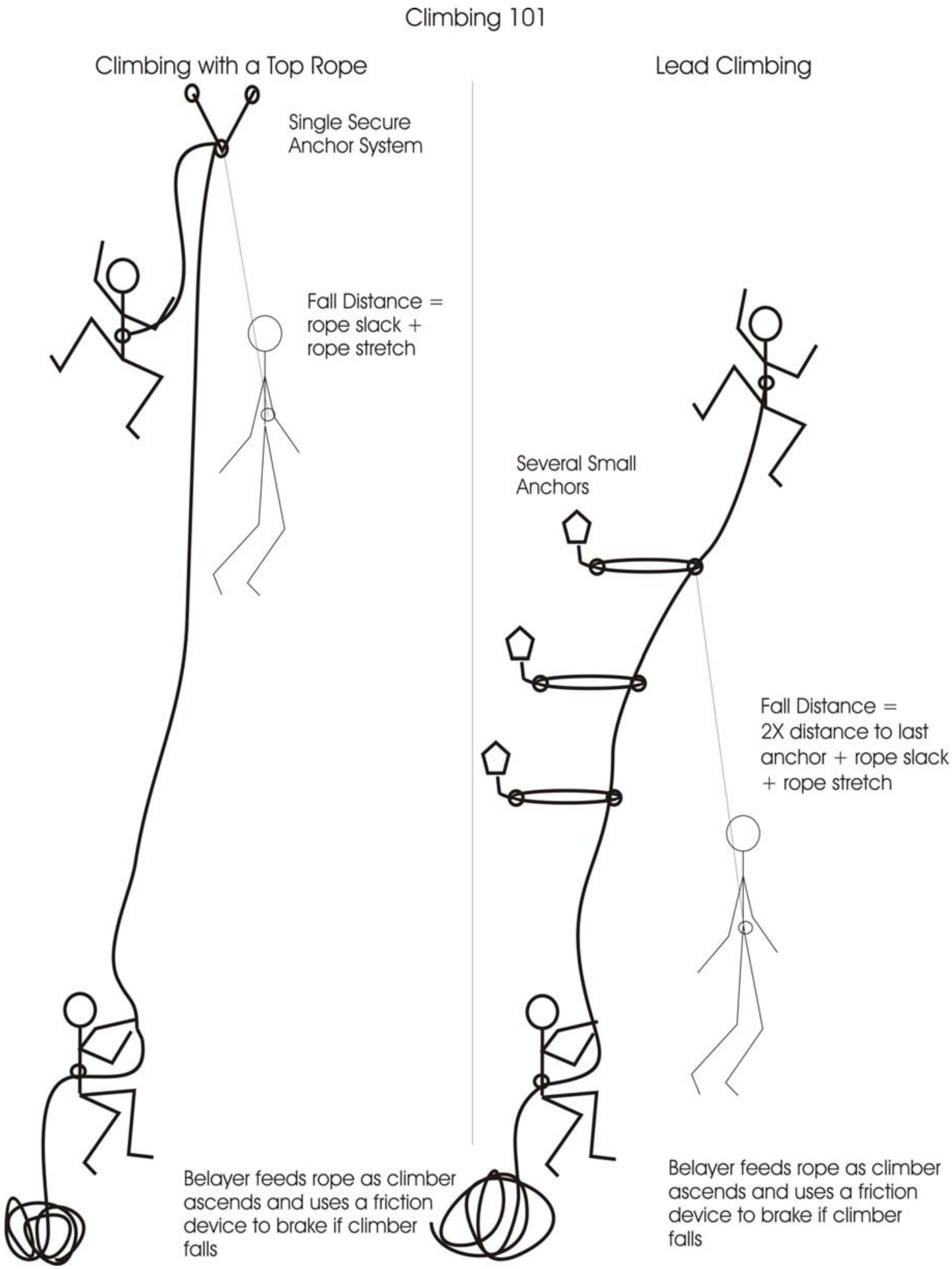
For the series vs. parallel forces demo, set up the apparatus below in two ways: first using springs and second using spring scales. When string 3 is cut, the mass will be held by two parallel springs instead of two springs in series. The mass will fly upward dramatically. In the spring scale demo, the spring scales will read half of their original value.



Lesson Plan:

- Engage:
  Read narrative: A Day at the Gunks
  Series vs. Parallel Forces Demo using springs and spring scales
- Explore:
  Anchor systems I: Explore how anchor position affects forces
- Explain:
  Discuss Relationship between angle and forces
- Extend:
  Anchor systems II (The American Death Triangle): Investigate how the arrangement and interplay of anchor equipment (slings, anchors, carabiners) affect forces and climbing safety
- Evaluate:
  Evaluate a new anchor system using the knowledge learned in the previous sections of the lab

THE PHYSICS OF ROCK CLIMBING



Physics of Rock Climbing: A Day at the Gunks

Jean and Hallie climb out of their car at the “Gunks,” short for the Shawangunks Mountain Range in the Mohonk Preserve in New Paltz, NY. The park has beautiful trails that run along the base and ridge of a large granite cliff known as the Trapps. It is internationally known for climbing.

They split the gear to carry up the long path from the parking area. Hallie takes the rope bag and a gear sling, and Jean takes her rack full of slings, carabiners, and protection or “pro” for short. They each carry their own climbing shoes, helmets, harnesses, belay devices and locking carabiners. As they begin the hike, Jean wonders aloud how she got stuck carrying all the heavy stuff, but Hallie argues that she doesn’t have room because of all the extra stuff she brought: snacks, extra water, clothes for every type of weather, her crazy creek chair, survival kit, foot warmers and a flashlight.

Jean checks her guidebook and decides to try “Beginners Delight,” a 5.3, which will be challenging but not too taxing for the first climb of the day. They each put on their harnesses and helmets and attach a belay device, short lengths of cord, a locking carabiner (a climber’s all-purpose connector) and a chalk bag to their harnesses. Jean will lead, so she ties in to one end of the rope, slips her rack over her head changes into her climbing shoes.

Hallie’s job is to belay, a technique of controlling the rope so that Jean doesn’t fall very far. Hallie threads a loop of rope through her belay device and locking carabiner, then ties the other end of the rope to her harness. Jean asks, “Belay On?” and Hallie does a final check: her harness is secure, the rope is correctly threaded through the belay device, her carabiner is locked and she is sitting comfortably, holding the rope with both hands. She responds, “On Belay” and Jean approaches the cliff. “Climbing,” Jean says, and Hallie responds, “Climb on!” taking up the slack as Jean chalks her hands and reaches up for her first hand hold.

Jean is lead climbing, so every few feet she stops and puts in a piece of pro. She finds a crack that is tapered (wide at the top and narrow at the bottom) and chooses a hex, a simple hexagonal piece attached to a loop of wire, which lodges in the narrow part of the rock and is held in place by friction. She attaches a sling of webbing to the wire loop and pulls hard in the direction it would be pulled in the event of a fall. The hex holds, so she clips webbing to the rope with a carabiner and resumes her ascent.

Jean climbs with skill, using her hands to hold her body close to the rock face and using the strength in her legs to push herself up. She reserves strength by hanging on outstretched arms, using her skeletal frame rather than her muscles to hold her body weight. Her climbing shoes are soled in sticky rubber, which has an extremely high coefficient of friction on the granite surface of the cliff, and can find purchase on the slightest ridge or steepest incline.

Jean climbs carefully, placing pro wherever possible, since she knows that if she falls when leading, she will fall twice the distance from her last piece of pro, and then further due to rope slack and rope stretch.

Jean thoughtfully chooses each piece of pro to take advantage of features in the rock. Hexes fit well into cracks that are wider at some points than others, and are plentiful since they are inexpensive. Tri cams rock into a wider position when they are pulled. Spring loaded cams use springs to push against the edges of the crack, increasing the frictional force by increasing normal force as they are pulled.

Hallie belays smoothly, keeping her eyes on Jean. Her hands fall into an easy rhythm: pulling in the slack and never letting go with her brake hand. If Jean were to fall, Hallie would simply change the angle of the rope in her brake hand, and the friction of the rope passing through the belay device would allow her to hold Jean's weight with minimal force.

Before long, Jean has reached the ridge at the top and takes a moment to rest and appreciate the view before yelling, "Slack!" Hallie lets out some slack so that Jean can traverse to the best place to set an anchor for a top rope.

Jean investigates the features of the ledge, and creates an anchor system with three anchor points: a tree, a spring-loaded cam wedged into a crack and a nut wedged into another crack. She uses more slings and cord to make adjustments and attaches a second locking carabiner to complete the top rope anchor. She then uses another cord to attach her harness to the anchor and unties from the main rope. "Belay off!" she calls down to Hallie, who can now relax.

Jean threads the loose end of the climbing rope through the locking carabiner and pulls up all the slack. Hallie yells, "That's me!" when she feels Jean pulling on the rope attached to her. Now that the slack has been taken up, Jean threads a loop of climbing rope through her belay device and the locking carabiner attached to her harness.

Meanwhile, Hallie puts on her climbing shoes, chalks her hands and prepares to climb. "Belay on?" she asks Jean. Jean does a final check: She's anchored to the ledge, her carabiners are locked, and her harness is still fastened securely. She finds a comfortable place to sit, grips the rope with both hands and shouts, "On Belay!" Hallie begins to climb.

As a second, it is Hallie's job to clean the pitch. Since she is top rope climbing, she depends only on the three-point anchor system at the top and Jean's belaying. All the pro Jean placed on her way up is now extraneous, and Hallie needs to retrieve it.

As she climbs, Hallie strays off-course. Rather than climbing along the path of the rope, she veers foolishly to the right where the climbing is easier. Suddenly, she misjudges a handhold and slips. "Falling!" she yells, and Jean instantly pulls her brake hand back, stopping the rope. Hallie doesn't fall far, only the distance of the rope stretch plus a little slack; but since she has veered off course, she pendulums left.

When falling, the safest position is arms and legs outstretched to brace for impact against the cliff face. Hallie, in an inexperienced gut reaction, grabs the rope instead. She scrapes, rolls and bangs her way to a stop, hanging high above the ground but safe in her harness.

When the adrenaline wears off, Hallie examines her war wounds. She has a few bruises and scratches, but she has emerged from her first fall relatively unscathed. The dynamic rope cushioned her fall and the helmet protected her head.

"I'm OK," she calls to Jean. "Next time I'll remember to put my hands out and not to veer off course!" She resumes climbing.

Soon Hallie arrives at the top with a rack full of gear. Hallie uses cord to attach her harness to the anchor, and then tells Jean, "Off Belay." The two sit on the ledge and look out at the valley below. The trees are just beginning to turn and the sun warms them on this high ledge. Turkey vultures circle on warm thermals. It's a beautiful day at the Gunks!

Pre-lab:
Use <u>A Day at the Gunks</u> and Climbing 101 to define the following words:
Terms:
Belay

Lead climbing

Top Rope Climbing

Anchor

Equipment:
Carabiner

Sticky Rubber

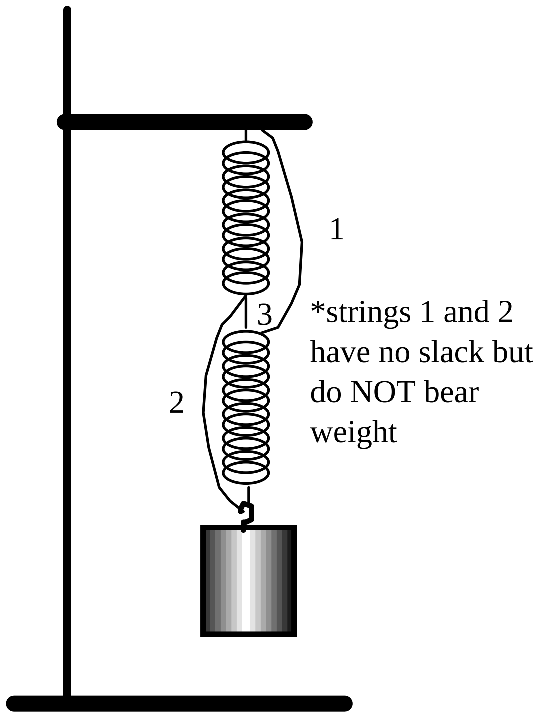
Sling

Hex

Tri-cam

Spring-loaded cam

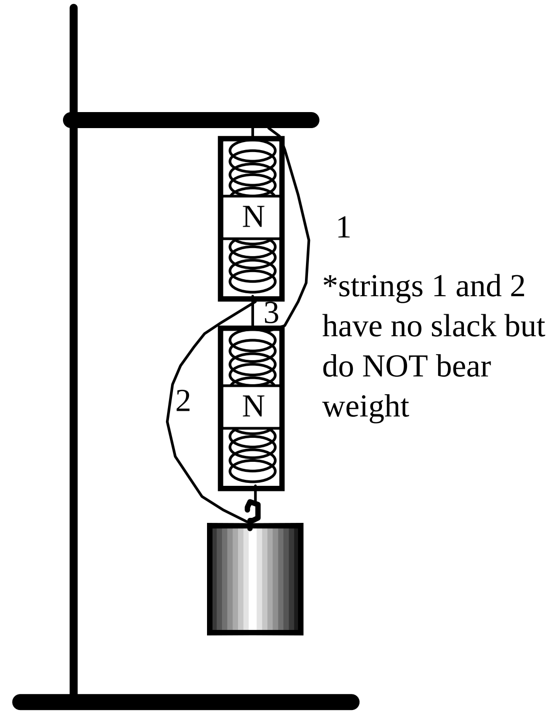
Series vs. Parallel Forces:
Examine the two setups shown below.



Predict what will happen to the weight string when 3 is cut.

What actually happened:

Explanation:



What do the two spring scales read before 3 is cut?

Predict what the spring scales will read after string 3 is cut:

What actually happened:

Explanation:

Anchor Systems I

Introduction: When rock climbing, anchors are used to guide ropes so that in the event of a fall, climbers will not experience dangerous forces. In top-rope climbing, a single set of anchors is established at the top of the climb. The climber depends on the belayer, who lets out slack allowing the climber to proceed, and brakes the rope in the event of a fall. The climber also depends on the anchor at the top of the climb, which guides the rope. If either the anchor or the belayer fails, the result can be catastrophic.

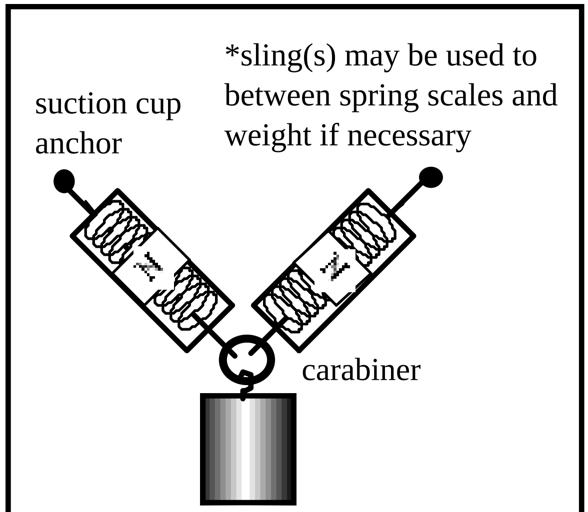
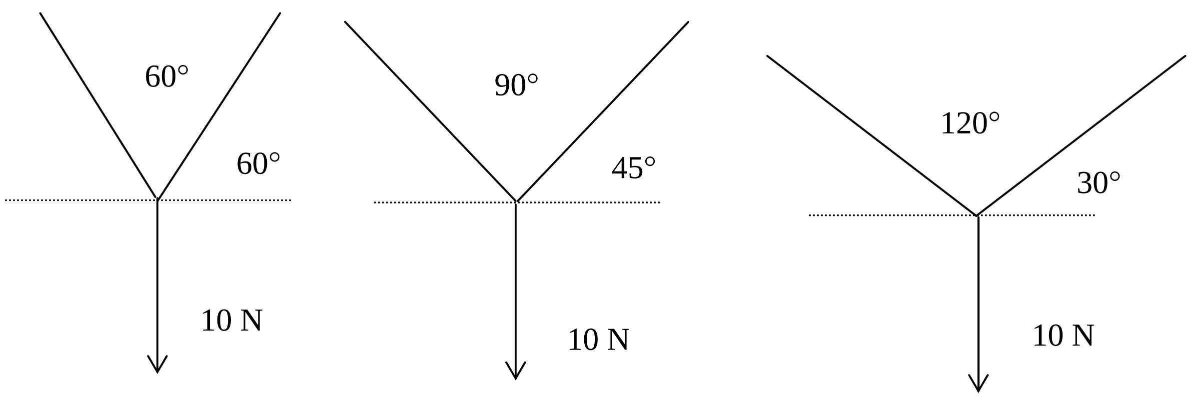


Figure 1

Purpose: To analyze several two-point anchor system to support a "climber," represented by a 10 N Weight. Use data to create a 'free body' vector diagram of the anchor system.

Procedure:

1. Use spring scales, suction cup hooks, and protractor to set up the following anchor/angle combination as shown in the figure below:



2. Measure and record the forces (not lengths) on each of the two anchors.
3. Using graph paper, construct a vector, free body diagram of each set up. (Scale: Use 1 cm = 1.0 N)

4. Use spring scales, suction cup hooks, and protractor to set up the following anchor/angle combination:
   - A: Rope angle at 90°, one anchor 20 cm vertically below the other (see illustration below)
   - B: Rope angle at 90°, one anchor 10 cm vertically below the other (see illustration below)

5. Measure the forces for each set up and record the angles from the horizontal to each rope.
6. Using graph paper, construct a vector free body diagram for each set up.
   (Scale: 1-cm = 1.0 N)
7. Using graph paper, construct a vector equilibrium diagram for each set up.
   (Scale: 1-cm = 1.0 N)
8. Answer question related to this part of the lab activity.

Analysis Questions:

1. Examine the anchor systems you created for supporting the "climber" (the 10 N weight). How did the angle between the two anchors affect the forces on the anchors?

2. Examine the three anchor systems with a 90° angle. How did the forces on the anchors compare when the anchors were in different vertical positions? What is the cause of this relationship?

3. Anchors systems are safest when they equalize forces. Explain why and give examples.

4. Though an average climber weighs about 600 N, a typical fall can exert a force of up to 12,000 N on the anchor system. What could account for this much larger force?

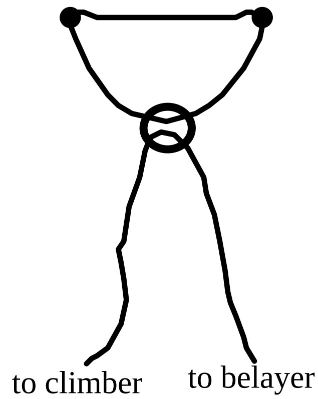
5. From what you have learned in this lab, design an ideal anchor system that minimizes the forces on the anchors. Draw your system below.

Extended task:
Using your new-found knowledge of anchors and top-rope climbing, use the ropes, suction cups, scales and carabiners to set-up a system which has three (3) rope anchors. Collect the data from your set-up and construct an equilibrium (head-to-tail) diagram on a piece of graph paper.

Anchor Systems II: The American Death Triangle

Introduction:

This lab examines the anchor arrangements used to guide ropes in top-rope climbing or belaying down. In actual climbing, one, two, three or more anchors are used, depending on the reliability of the anchor. One anchor may be acceptable for very sturdy anchor points such as trees, two may be acceptable and three is the standard for safety. In this lab we will be examining two-point anchor systems. The table below outlines the equipment we will be using and what it represents.



Term:	Equipment used in lab:	Equipment used in climbing:
Anchors	nuts, bolts, screws, trees, cams	hooks mounted on suction cups
Carabiners	climbing carabiners	small non-climbing carabiners
Slings	slings made of sturdy webbing	slings made of rope
Climber	climber	10 N weight

Purpose:

To investigate how the arrangement and interplay of anchor equipment (slings, anchors, carabiners) affect forces and climbing safety

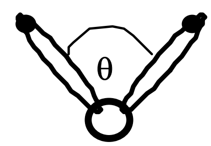


Figure 1

Procedure:

For each anchor system illustrated in the chart:

1. Using slings and carabiners, set up the anchor system illustrated in the chart.
2. Attach a 10 N weight to the carabiner to simulate the weight of a climber as shown.
3. Adjust the suction cups until the angle between forces is 60°. Keep this angle at 60° throughout the experiment. (See Figure 1)
4. Examine each anchor arrangement according to the criteria listed on the chart. Use spring scales where necessary to measure forces (See Figure 2)
5. Write your observations and measurements in the chart
6. Write a small + or - to indicate whether this anchor has an advantage or disadvantage when judged according to this criteria
7. Make sure anchor is properly set up before moving on
8. At the last station, examine your observations and rank the anchor systems, from 1 (best) to 4 (worst).

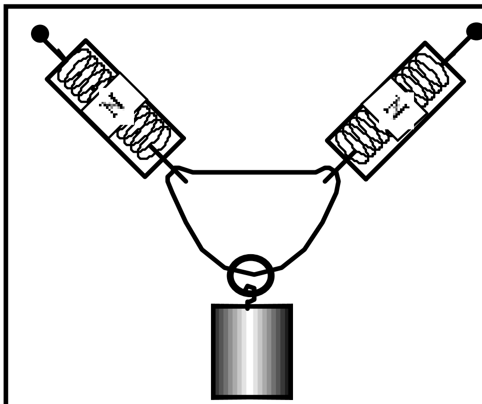
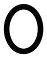
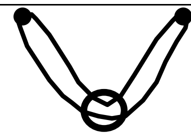
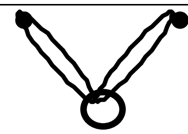
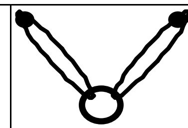
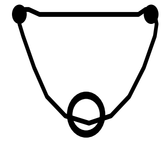


Figure2

Anchor System  anchors  carabiners	 One sling untwisted	 One sling in figure eight with carabiner through each side of the figure eight	 Two separate slings	 American Death Triangle: One sling hooked in a triangle as shown
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Forces on Each Anchor: Use spring scales to examine the forces on each of the anchors. Remember to adjust the anchors to keep the angle between the forces at a constant 60°.				
Are Forces Self Equalizing? Anchors are safest when weight is equally distributed. Move position of the climber back and forth. Are the forces equal on each side?				
Shock Weighting During Anchor Failure: Using spring scales to measure forces, simulate anchor failure by unhooking one sling and dropping it. What happens to the climber? The force on the remaining anchor?				
Rank subjective:				

Conclusion:
What did you consider to be the safest anchor system? Back up your choice according to each of the criteria listed above.

Evaluation question:
Each of the anchor systems examined in the lab is designed to have a rope passed through the carabiner when climbing as shown in figure 1. Figure 2 illustrates a simpler system that does not use a carabiner. What are the advantages and disadvantages of this carabiner-less anchor system? Explain your answer according to the criteria examined in this lab and any other criteria you might think of.

Figure 1

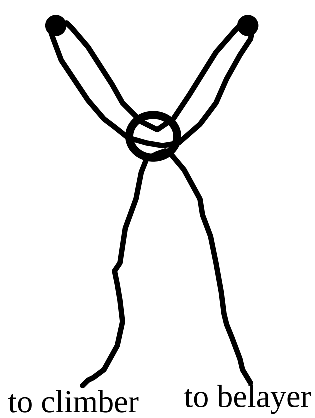

Figure 2