CNS Institute for Physics Teachers

Title:	**The Physics of Rock Climbing**
Original: **Revision:**	28 October 2005 26 May 2010
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:	M1.1 Use algebraic and geometric representations to describe and compare data. Use scaled diagrams to represent and manipulate vector quantities. Represent physical quantities in graphical form. Manipulate equations to solve for unknowns. 5.1j When the net force on a system is zero, the system is in equilibrium 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
Special Notes:	**The Physics of Rock Climbing** is available as a kit from the CIPT Equipment Lending Library, www.cns.cornell.edu/cipt/. Special thanks to Jean Amodeo, technicaladvisor/climbing buddy.

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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 class periods

Teacher Preparation Time:
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
- 1 kg weight (put armaflex cover on weight to prevent it from scratching surfaces)
- dry erase marker (optional)
- 2 small carabiners (not meant for climbing)
- 3 slings of rope (1/8" or larger braided rope cut into 18" lengths and tied into loops)
- 3 suction cups with hooks
- protractor (ideally with line level attached and 60°, 90° and 120° angles marked centered on vertical)
- 3 20 N spring scales

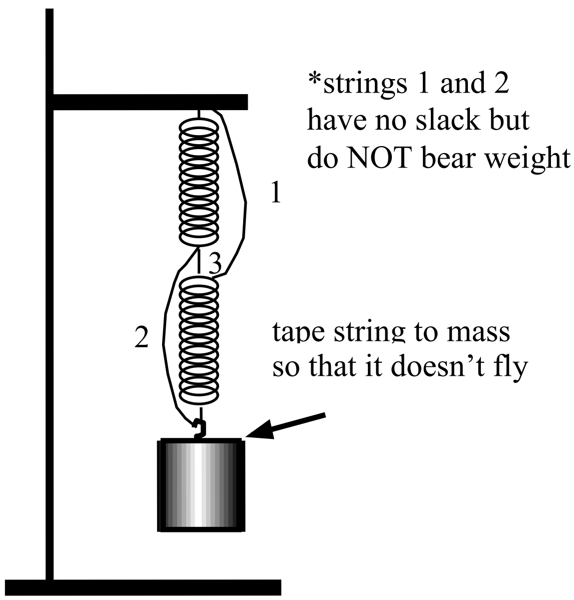
Additional materials needed for series vs. parallel forces demo:

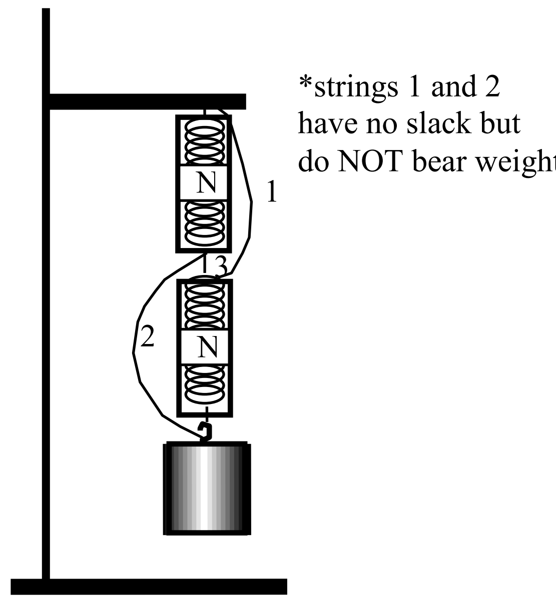
- 2 harmonic motion springs
- string
- ringstand with clamp
- tape

Tips for Teachers:
Set the hook of the locking anchor (suction cup) in line with the axis of the spring scale.
If you don't, the locking anchor may twist and pull off the wall.

A Youtube video produced by CIPT alumni Christian Fracchia and Leila Madani entitled the Physics of Rock Climbing is available at:
Part 1 - http://www.youtube.com/watch?v=VSHxa9WI7Qw
Part 2 - http://www.youtube.com/watch?v=T1cXpqCWtTM&NR=1

Series vs. Parallel Forces Demo
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

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

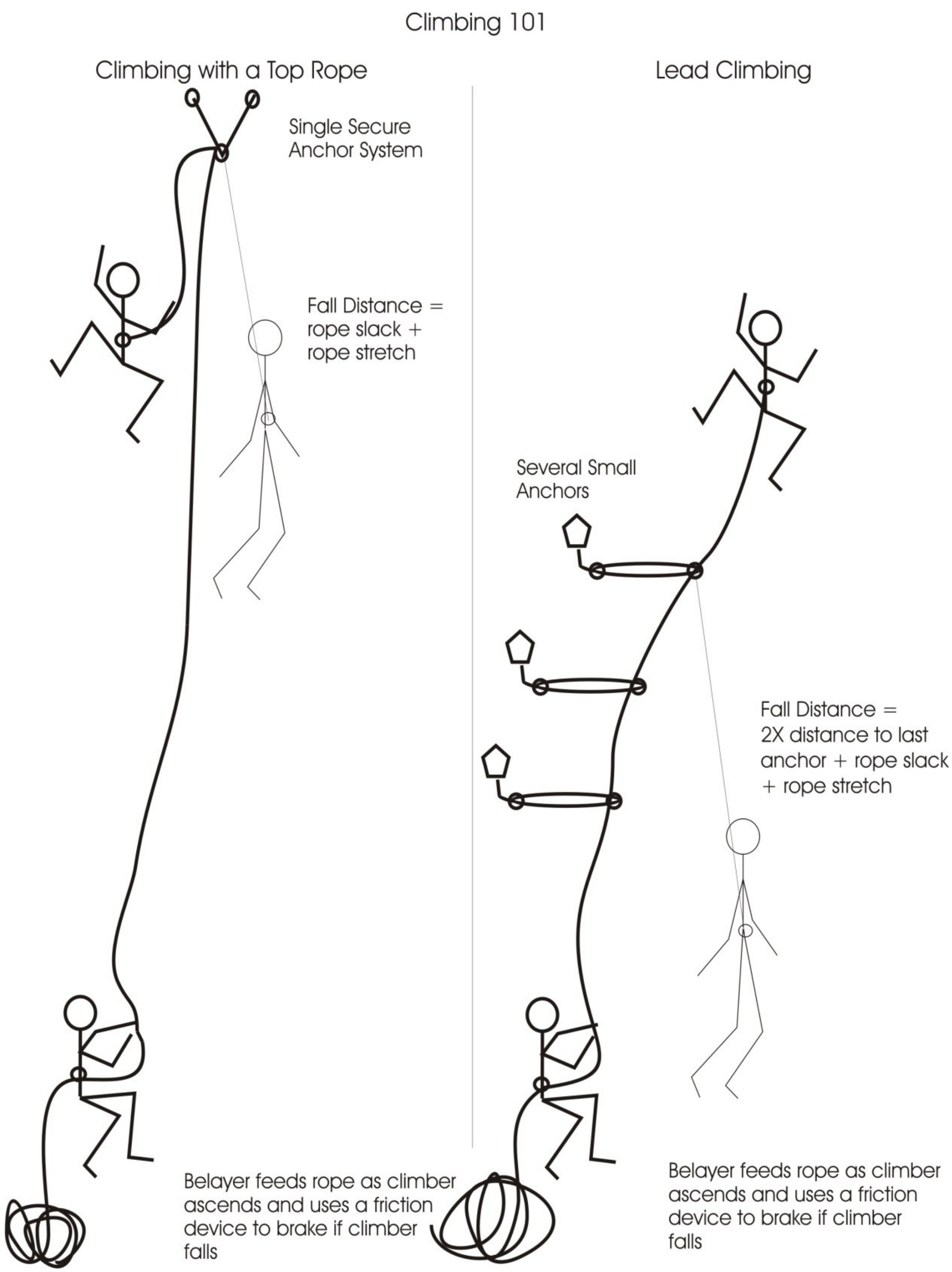
Answers to Questions: *send email to cipt_contact@cornell.edu to request answers*

Equipment

Item No.	Quantity	
1	1	DVD, CD or video tape of *The Basics*
2	1	Masking tape
3	1	Protractor with line level attached
4	1	Weight – 1kg
5	1	Rubber cover for weight
6	1	Right angle clamp
7	1	Dry erase marker
8	2	Carabiner
9	3	Twine loops
10	3	Suction cups
11	3	20 N spring scales
12	1	Ring stand
13	1	Meter stick
Not shown	2	Harmonic motion springs

THE PHYSICS OF ROCK CLIMBING

Pre-Lab



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!

The Physics of Rock Climbing

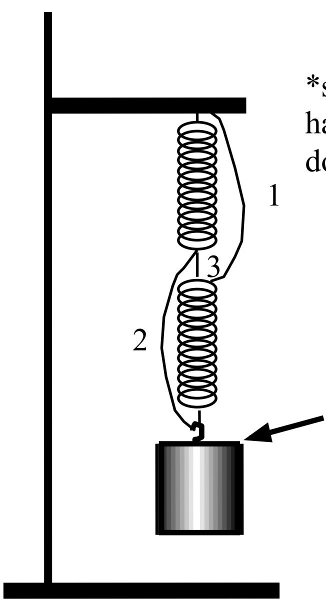
Pre-lab:

Read A Day at the Gunks and Climbing 101 to define the following words on the Student Data Sheets.

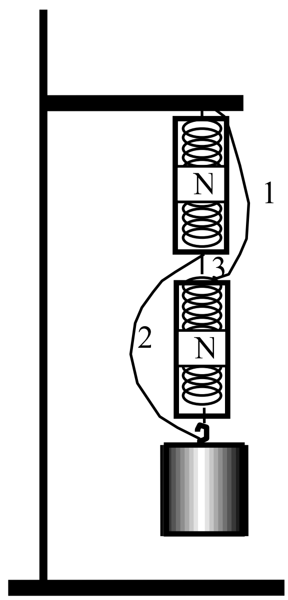
Terms:
Belay
Lead climbing
Top Rope Climbing
Anchor

Equipment:
Carabiner
Sticky Rubber
Sling
Hex
Tri-cam
Spring-loaded cam

Series vs. Parallel Forces Demonstration:
(Figure 1 has two springs and Figure 2 has two spring scales)



*strings 1 and 2 have no slack but do NOT bear weight



*strings 1 and 2 have no slack but do NOT bear weight

- What will happen when you cut string #3 in Figure 1? Discuss with your lab partner and write your prediction on the Student Data Sheet.
- Suppose a 1 kg weight is hanging in Figure 2. What will the spring scales read before and after you cut string #3? Discuss with your lab partner and write your prediction on the Student Data Sheet.
- Watch the demonstrations. Record what actually happened on the Student Data Sheet.
- Discuss discrepancies between your prediction and observations with your lab partner.

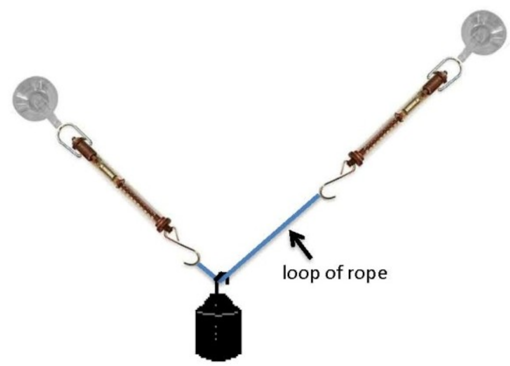
Anchor Systems I

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.

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

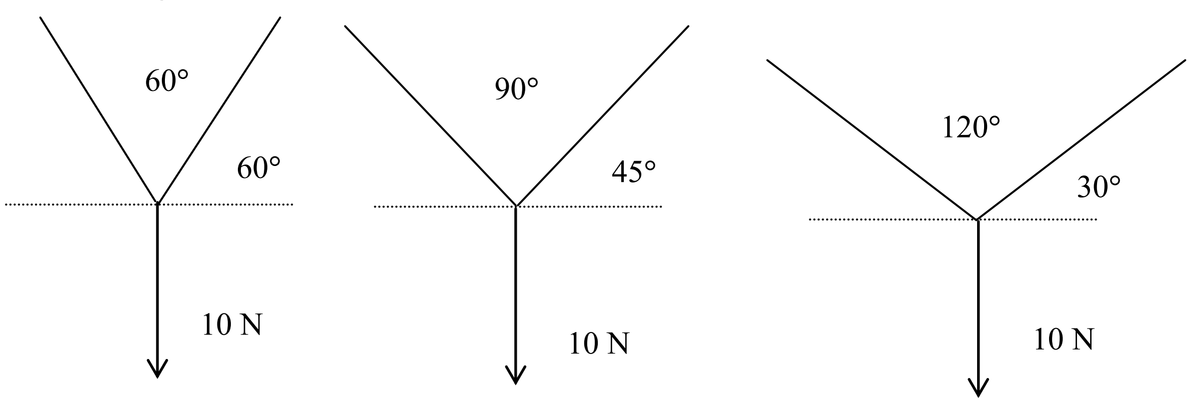
Procedure:

NOTE: Set the hook of the locking anchor (suction cup) in line with the axis of the spring scale. If you don't, then the suction cup may twist and pull off the wall. Attach spring scales to loop of rope. Hang weight from rope.



Set-up #1: 2 Anchors, Same Height

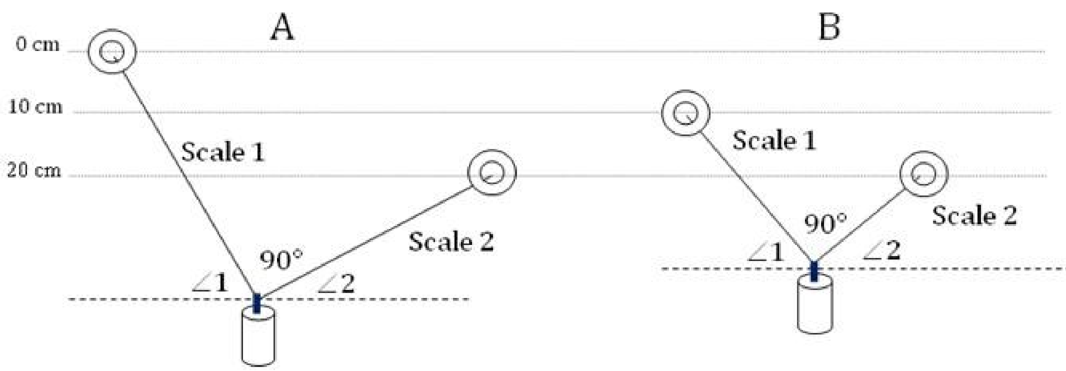
- Use spring scales, suction cup hooks, and protractor to set up the following anchor/angle combination as shown in the figure below with the spring scales at the same height:



- Record the force on the spring scales for each of the two anchors in the table in the Student Data Section.
- Use the graph paper in the Student Data Section, construct a scaled vector, free body diagram of each set up. (Scale: Use 1 square length = 2.0 N)

Set-up #2: 2 Anchors, Unequal Heights

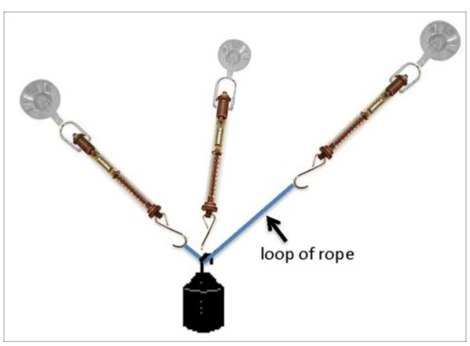
- Use suction cup hooks, spring scales, a loop of rope and protractor to set up the following two-anchor systems shown in the illustration below:
  - A: Rope angle at 90°, one anchor 20 cm vertically below the other
  - B: Rope angle at 90°, one anchor 10 cm vertically below the other



- Measure the forces for each set up and record the angles from the horizontal to each rope in the table on the Student Data Sheet.
- Using graph paper, construct a vector free body diagram for each set up. (Scale: Use 1 square length = 2.0 N)
- Using graph paper, construct a vector equilibrium diagram for each set up. (Scale: Use 1 square length = 2.0 N)

Set-up #3: 3 Anchors

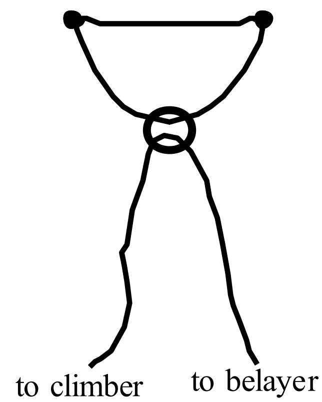
- Use spring scales, suction cup hooks, and a protractor to set up the following three-anchor system shown in the illustration below. Make sure there is force on all three spring scales.



- Measure the forces on each spring scale and the angles from the horizontal. Record your data in the table on the Student Data Sheet.
- Answer Analysis Questions in the Student Data Section

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 climbing:	Equipment used in lab:
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

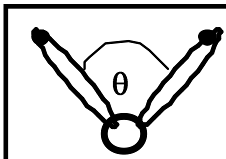


Figure 1

Procedure:
For each anchor system illustrated in the chart:
- Using slings and carabiners, set up the anchor system illustrated in the chart.
- Attach a 10 N weight to the carabiner to simulate the weight of a climber as shown.
- Adjust the suction cups until the angle between forces is 60°. Keep this angle at 60° throughout the experiment. (See Figure 1)
- Examine each anchor arrangement according to the criteria listed on the chart. Use spring scales where necessary to measure forces (See Figure 2)
- Write your observations and measurements in the chart in the Student Data Section.
- Write a small + or - to indicate whether this anchor has an advantage or disadvantage when judged according to this criteria in the Student Data Section.

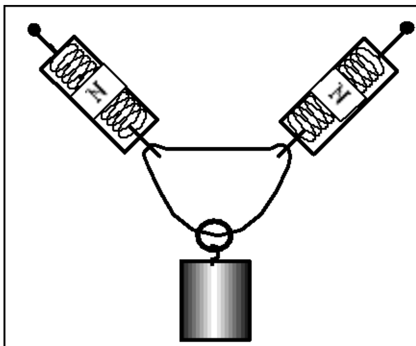
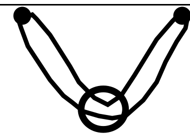
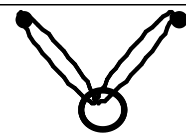
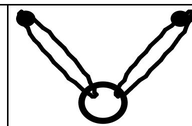
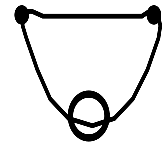


Figure2

- Make sure anchor is properly set up before moving on.
- At the last station, examine your observations and rank the anchor systems, from 1 (best) to 4 (worst) in the Student Data Section.

Anchor System ● anchors O 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

PHYSICS OF ROCK CLIMBING
Student Data Sheets

<u>Pre-Lab:</u>
Define the following TERMS:
Belay

Lead climbing

Top Rope Climbing

Anchor

Define the following EQUIPMENT:
Carabiner

Sticky Rubber

Sling

Hex

Tri-cam

Spring-loaded cam

Series vs. Parallel Forces Demo:

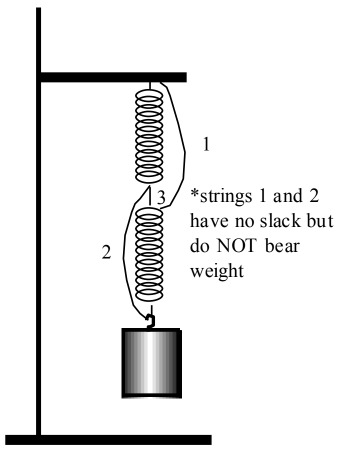


Figure 1 (2 springs)

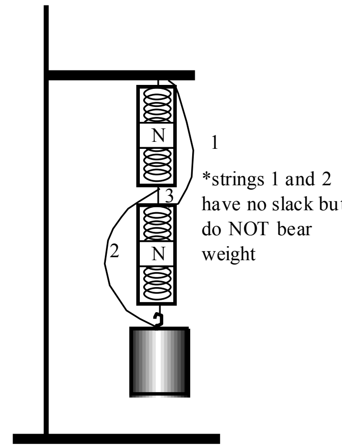


Figure 2 (2 spring scales)

Figure 1
Predict what will happen to the weight when string when 3 is cut.

What actually happened?

Explanation:

Figure 2
Predict what the two spring scales will read before 3 is cut?

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

What did the spring scales actually read?

Explanation:

Anchor Systems I

Set-up #1

Record the force on the spring scales (not lengths) for each of the two anchors.

Angle	Force (N)
60°	
90°	
120°	

Using the graph paper below, construct a vector, free body diagram of each set up.
(Scale: Use 1 square length = 2.0 N)

Set-up #2
Record the force on the spring scales and angles for systems A and B with anchors at unequal heights.

System	Force 1 (N)	∠1 (º)	Force 2 (N)	∠2 (º)
A				
B				

Using the graph paper below, construct a vector free body diagram of each set up. (Scale: Use 1 square length = 2N)

Using the graph paper below, construct a vector equilibrium diagram of each set up. (Scale: Use 1 square length = 2N)

Set-up #3

Record the force on the spring scales and angles for system B with three anchors.

Force 1 (N)	∠1 (º)	Force 2 (N)	∠2 (º)	Force 3 (N)	∠3 (º)

Using the graph paper below, construct a vector free body diagram and vector equilibrium diagram for the three anchor set up.
(Scale: Use 1 square length = 2N)

Analysis Questions:

1. Examine the anchor systems at equal height and differing angle that you created for supporting the "climber" (the 10 N weight). What is the trend between angle and force on the spring scale?

2. Assume this system is a model for a climber hanging from both hands. If the climber had to hold on for a long time, how should he/she position his/her hands and why?

3. 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?

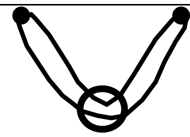
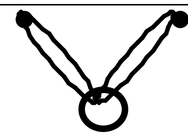
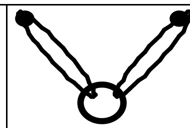
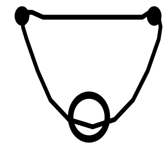
4. Anchor systems are safest when they equalize forces. Explain why and give examples.

5. Compare the two and three anchor system. What is the effect of adding a third anchor? When might it make sense to do this in a real life situation?

6. 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?

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

Anchor Systems II: The American Death Triangle

Anchor System ● anchors O 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.				
Anchor Failure: Simulate anchor failure by unhooking one of the slings from the anchor. What happens to the climber? The other anchor?				
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

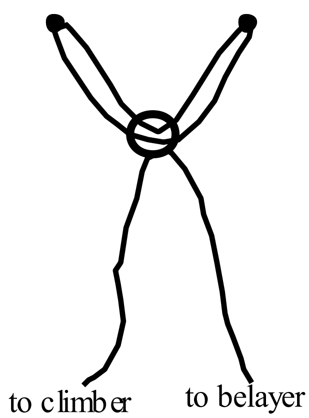


Figure 2