The Science of Archery

Godai Katsunaga

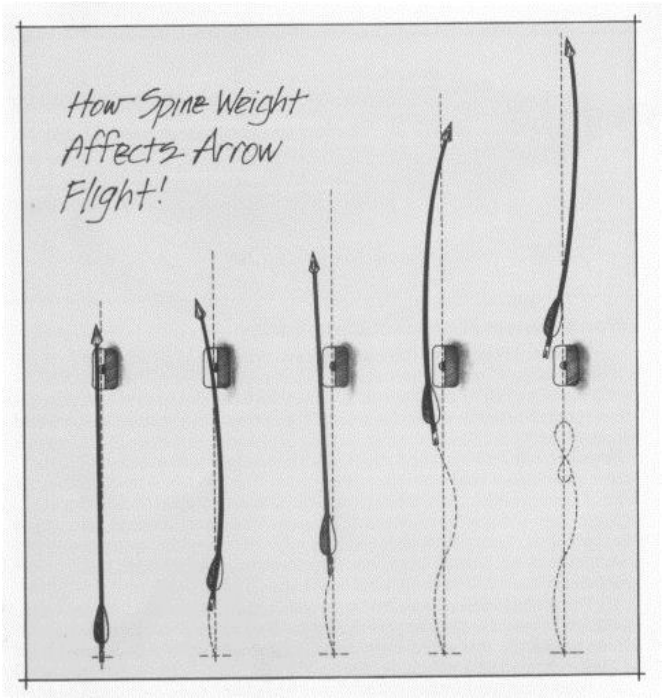
Purpose

To provide insight into the physics of arrow flight and show how archers adapt their equipment to maximize effectiveness.

Archery

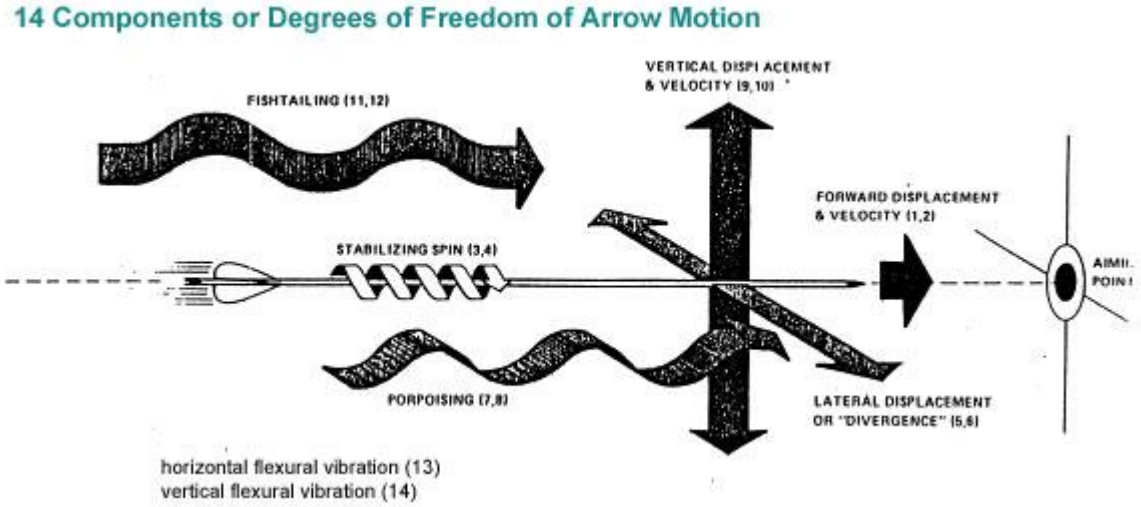
Archery is one of the events that many people think is just an easy martial activity where you pick up any bow and any arrows and shoot. What many people do not realize is that the forces acting on an arrow in flight are many and that an archer must account for these forces to be accurate.

The string generates a high force on release that acts on the arrow, it rapidly accelerates and because it acts in the direction of the arrow shaft, the shaft begins to oscillate or fishtail back and forth. We call this the archer's paradox. Archer's must take into consideration the aerodynamic flight of the arrow, Drag, Forward of Center, stability, gravity and weight all affects the arrows accuracy and range. I will try to explain the basic of the science of archer and steps that archers go through to be the best at their craft.



Drawing of an arrow at the moment of release.

Forces



Drawing from Archery Equipment.Org

Looking at the image above, there are 14 forces acting on and an arrow in flight. Archers try to minimize those forces that lead to inaccurate arrow flight while trying to maximize those forces that increase accuracy.

Forward displacement and velocity
This is determined by the power of the bow, the weight of the arrow. For any given bow, the only changes the archer can do are change the weight of the arrow and reduce the drag.

Stabilizing Spin
This is determined by the size of the fletching, offset and helical or straight fletched. More spin means more drag but more stability.

Lateral Displacement
This can be affected by brace height, and rest position as well as dynamic spine of the arrow. Archer's can tune the bow to minimize these forces.

Porpoising
This can be affected by nock height. The nocking point for any archer is determined by the basic technique of the archer and the bow they are using, for most archers this does not change over time.

Vertical Displacement and Velocity
Both gravity and drag affect this force. Gravity being a constant the archer can only affect drag. Gravity does have an effect on up hill or down hill shooting.

Fishtailing
This force can be affected by brace height, dynamic spine and rest position. Archers tune the bow to minimize the affect of this force.

Arrow Spine

In SCA archery we use wooden arrows in our archery events. Unlike aluminum, fiberglass or carbon shafts, wooden arrows are not “manufactured”, thus the weight and strength is determined by the diameter of the shaft and the density of the wood. Many woods are used in arrow construction; the most popular are Port Orford Cedar and Sitka Spruce.

Arrows must be made for the bow and the archer that will shoot them, every bow has a draw weight that indicates the strength in pounds that is required to hold the bow at full draw, also each archer has a different draw length that affect the draw weight and also the arrow length. An arrow that is too weak will break when the archer shoots it, while one that is to strong will not fly straight. Archers call this strength the spine weight, or "stiffness" of the wood shaft, is the most important characteristic of the wooden arrow shaft.

STATIC SPINE is the stiffness of the arrow and its resistance to bending. To determine static spine, the arrow is supported a two points a known distance apart, usually 26 inches, and a 2 pound force is applied to the center of the distance through a weight. The amount of displacement of the center point, how far the arrow bends, determines the spine. There are tables or a gauge that will convert shaft deflection into pounds, a more usual description of the stiffness. This conversion can also be done using the simple formula Spine (in pounds) equals 26 divided by the deflection in inches. Thus a shaft bends half an inch then is it has a 52 pound spine measurement. Arrows with a high spine will not bend as much as arrows with a low spine. Adding an inch to the arrow length will decrease the shaft spine by 3 to 5 pounds, while shortening a shaft will add 2 to 3 pounds of static spine.

DYNAMIC SPINE is how much the arrow bends when fired. This depends upon the static spine, string force, fletching, nock weight, point weight and overall length of the arrow. Arrows are often described as "Weak" or "Stiff"; these terms describe the dynamic spine of an arrow on a particular bow.

It is more difficult to determine dynamic spine than static spine because so many variables affect the force acting down the shaft. There are some dynamic spine calculators, but the only real way to check an arrows flight is to shoot the arrow off the bow that it is being used for. Arrow fired off a right handed bow hit to the left, they may be to stiff, if they hit to the right, they may be too weak.

Dynamic spine can also be affected by point weight. A heavier point effectively weakens the arrow and a lighter point means a stiffer effective arrow. Remember Newton’s laws of motion, an object that is at rest will stay at rest unless an external force acts upon it and to every action there is always an equal and opposite reaction. Thus your point is the object. 125 grain is considered the standard by many archers, so increasing your lowering your point tip will change the spine of the arrow.

Arrow length also affects dynamic spine. For any given spine, a shorter arrow is stiffer than a longer arrow. Therefore shortening an arrow will stiffen it, while a longer arrow will weaken the spine.

In conclusion, the arrow must be just right to match the forces that act on the arrow at release, the draw weight of the bow, the draw length, and the archer's shooting technique. This is just the first step determining the right arrow for any given archer.

Aerodynamics

First we will look at some basics, the more powerful the bow the faster it throws the arrow, thus the less time it is in the air, the more direct route to the target and the less it is affected by wind and atmospheric conditions. The instant an arrow leaves the string it is at its maximum velocity. In tests done with both heavy arrows and light arrows, we find that the light arrows slow down at a faster rate then the heavy arrow, about 40% faster. A heavy arrow will also maintain kinetic energy better than light arrows at any given distance.

Example: 326 grain and a 580 grain arrow fired from the same bow.

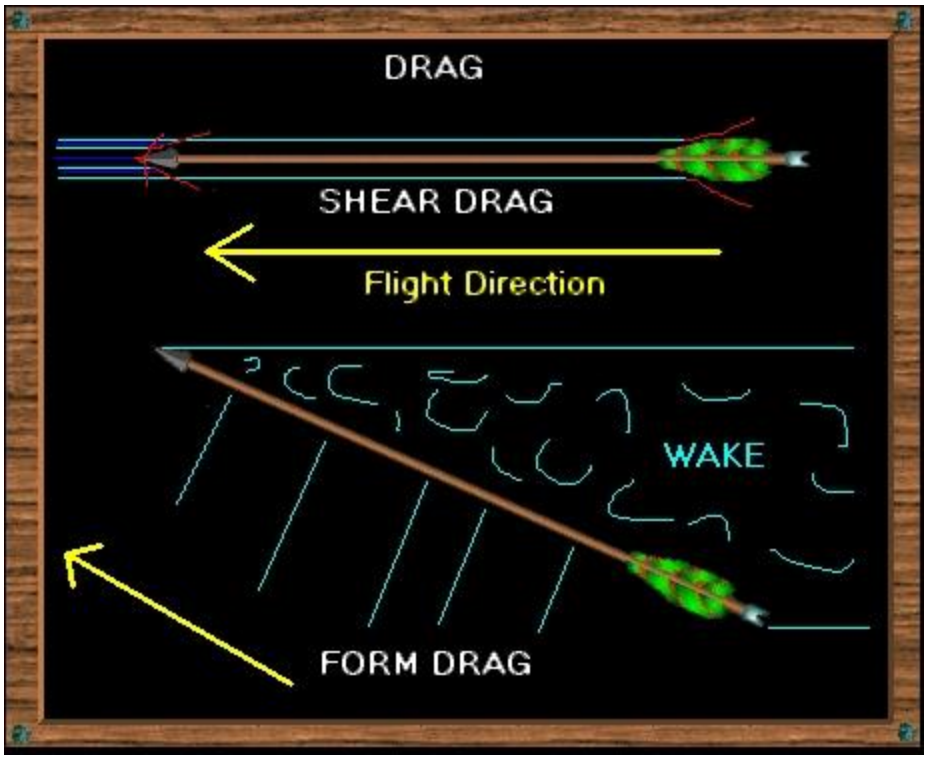
326gr Speed (fps)	326gr KE	Yards	580gr KE	580gr Speed (fps)
316	72 ft/lbs	0	76 ft/lbs	243
308	68 ft/lbs	10	73 ft/lbs	239
299	64 ft/lbs	20	71 ft/lbs	235

Net loss for the light arrow was 17 fps or 5.3% of initial speed. The heavy arrow only lost 8 fps over the same distance or 3.2 % of initial speed.

This shows that a lighter arrow will have a higher initial velocity but a slightly heavier arrow will push through the air better at the expense of having to aim higher at longer distances. This is a balance that every archer must understand and take into account with the type of shooting they will be doing.

For most archers there is a limit to our strength, thus there is a limit to what we can pull, in the type of bows used in the SCA. Remember that a 40 pound bow means that the archer is holding 40 pounds of force when at full draw trying to stabilize the bow and aim. Modern compound bows have a let down weight that is determined by the cam shape and size, an example may be a bow of 80 pounds is only 30 pounds after the cam "let down", thus a compound shooter will shot a more powerful bow than most stick bow shooters.

As soon as the arrow leaves the bow forces start to affect the flight of the arrow, If we minimize the forces with proper tuning we get down to the most basic forces of drag and gravity. The archer can not affect gravity so this will be removed from our discussion.



Drawing from Physics of Archery

SHEAR DRAG is a result of the arrow's moving through the air. Energy is expended to move the air out of the way so that the arrow can pass. As the arrow pushes on the air, the air pushes on the arrow, thus resistance to the movement of the arrow or drag. Shear drag is proportional to the velocity of the object and the size and shape of the object.

FORM DRAG results in a force pushing perpendicular to the direction of flight when applied along side shear drag, sometimes called lift. A layer of turbulent, lower-pressure air is caused by the movement of the arrow through the air creating a wake. This wake steals energy from the arrow but creates a force which pushes the arrow upwards like the lift of an airplane; perpendicular to its path of flight. Archers can affect these two forces in several ways by changing the way arrows are made.

Drag acting upon the fletching stabilizes the arrow in flight. Larger fletching will slow the arrow down with more shear drag, but respond better to form drag. This makes the arrow more stable and increases accuracy at shorter distances but effect how far the arrow can fly. Smaller fletching is less affected by shear drag and won't slow the arrow down as much, but it is more likely to wobble in the air and have less accuracy at shorter distances but the arrow will fly further. Again a balance must be reached between the size of the fletching and the length of the arrow and the style of shooting.

FORWARD OF CENTER (FOC) is another factor that affects the arrow flight. FOC is measured in how far from the center of the arrow the balance point is located; it is usually described as a percentage.

An arrow that is "tip-light" or with neutral FOC will remain a little more level in flight and will actually plane or sail along a flatter trajectory than an arrow of the same weight with a heavier nose or higher FOC would. The trade off is that the closer the center of gravity gets to the physical center of the arrow, the less stable the arrow becomes. An arrow pivots around its center of mass (balance point) and the farther the balance point is from the fletching, the more leverage the fletching will have and the quicker it can bring the arrow back on line. The shorter the arrow one shoots, the higher the FOC should be because shorter arrows are inherently less stable in flight.

A finger release also adds to arrow instability, especially in initial flight, so finger shooters find that a high FOC is beneficial.

Another benefit to a high FOC is that the arrow will stabilize from relative smaller fletching thus less drag and longer shots.

While there doesn't seem to be a magic number for FOC, it is generally accepted that the optimal FOC balance for an arrow is somewhere between 8% and 16%.

Feathers

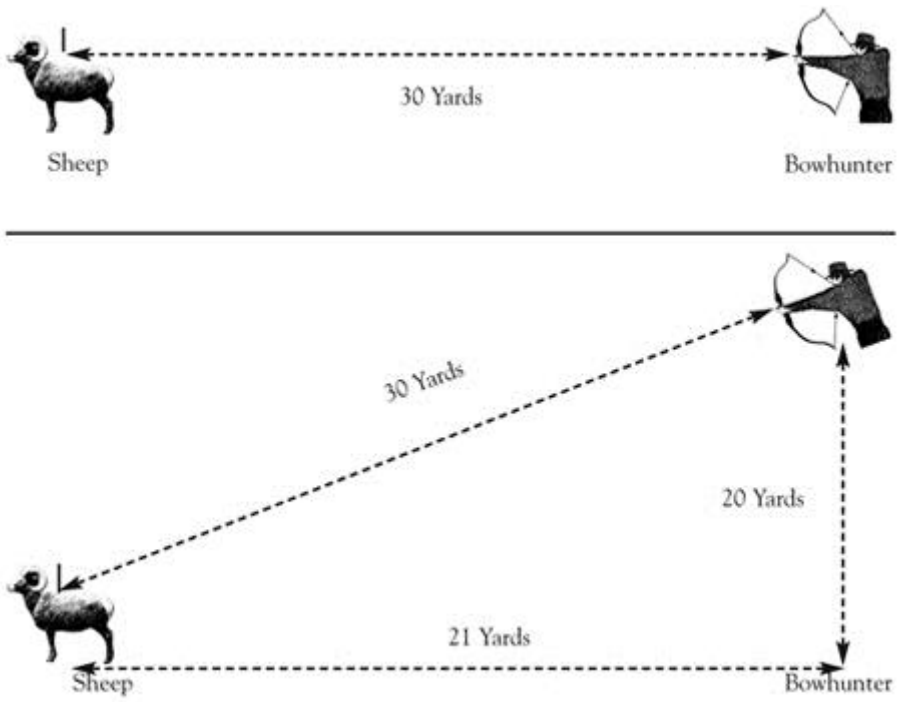
All arrows used in SCA shoots must use feathers. In order for the fletching to correct the flight of the arrow, they must move the arrow into a straighter flight path by rotating the shaft about the center of balance.

Feather shape and size can have an incredible effect on arrow performance. Longer feathers will produce more spin, faster stabilization and more short range accuracy. Short feathers produce less drag, thus maintain velocity better and are often used on flight arrows where accuracy is not as important.

Shield feathers are higher profile and stabilize faster while parabolic will be faster down range. Feather makes have conducted flight tests that have shown there is no difference in speed between parabolic and shield feathers of the same length out to about 40 yards. While Banana shaped feathers provided maximum stabilization and were designed for heavy arrows at short range. Feather selection should be tuned to the style of shooting that the archer is doing. Some archers go so far as have arrows with different feathers in their quiver.

Up Hill and Down Hill Shooting

As we talked about gravity earlier, it is a constant and we can not change the effect it has on an arrows flight. Gravity does come into play when shooting at an angle. Learning to shoot effectively up and down hills is another aspect of the science of archery.



Drawing from Traditional Bowhunter

As you can see from the drawing the effective distance when shooting up hill or down hill is not the same. Simple physics show that gravity only affects the arrow over the actual linier distance from the archery to the target. So many archers aim for the target taking into account the perceived distance and miss high.

Conclusion

Archery is not just picking up a bow, some arrows and shooting.
Archers test many factors to produce the most accurate bow and arrow combination. The type of wood the arrow is made from, the spine, weight, what type of fletching to use and how heavy the point must be to get the correct FOC.
The wood that the arrow is made from and the length of the arrow both affects the weight of the arrow and the spine.
The size and shape of the fletching affect the amount of drag and the stability of the arrows in flight.
The weight of the arrow components determines the FOC and the stability of the arrow.

Talk to the best archers and you will find that they have spent almost as much time on getting the arrows right for their bow as they have spent in practicing. There is no perfect solution, so most of us spend time trying different combinations to get that almost perfect setup that will when combined with proper shooting form give us the best overall accuracy.

References

Shooting the Stickbow by Anthony Camera
Published by Virtualbookworm.com Publishing, 2008

Beginners Guide to Traditional Archery by Brian J. Sorrells
Published by Stackpole Books, 2004.

Web sites

http://www.addictedtoarchery.com/arrow-spine.aspx

http://www.real-world-physics-problems.com/physics-of-archery.html

http://www.archeryequipment.org/flight-mechanics-of-an-arrow/

http://mrfizzix.com/archery/

http://www.physicsofarchery.webs.com/

http://www.tradbow.com/

http://margo.student.utwente.nl/sagi/artikel/bas/archghh.html

http://www.meta-synthesis.com/archery/archery.html