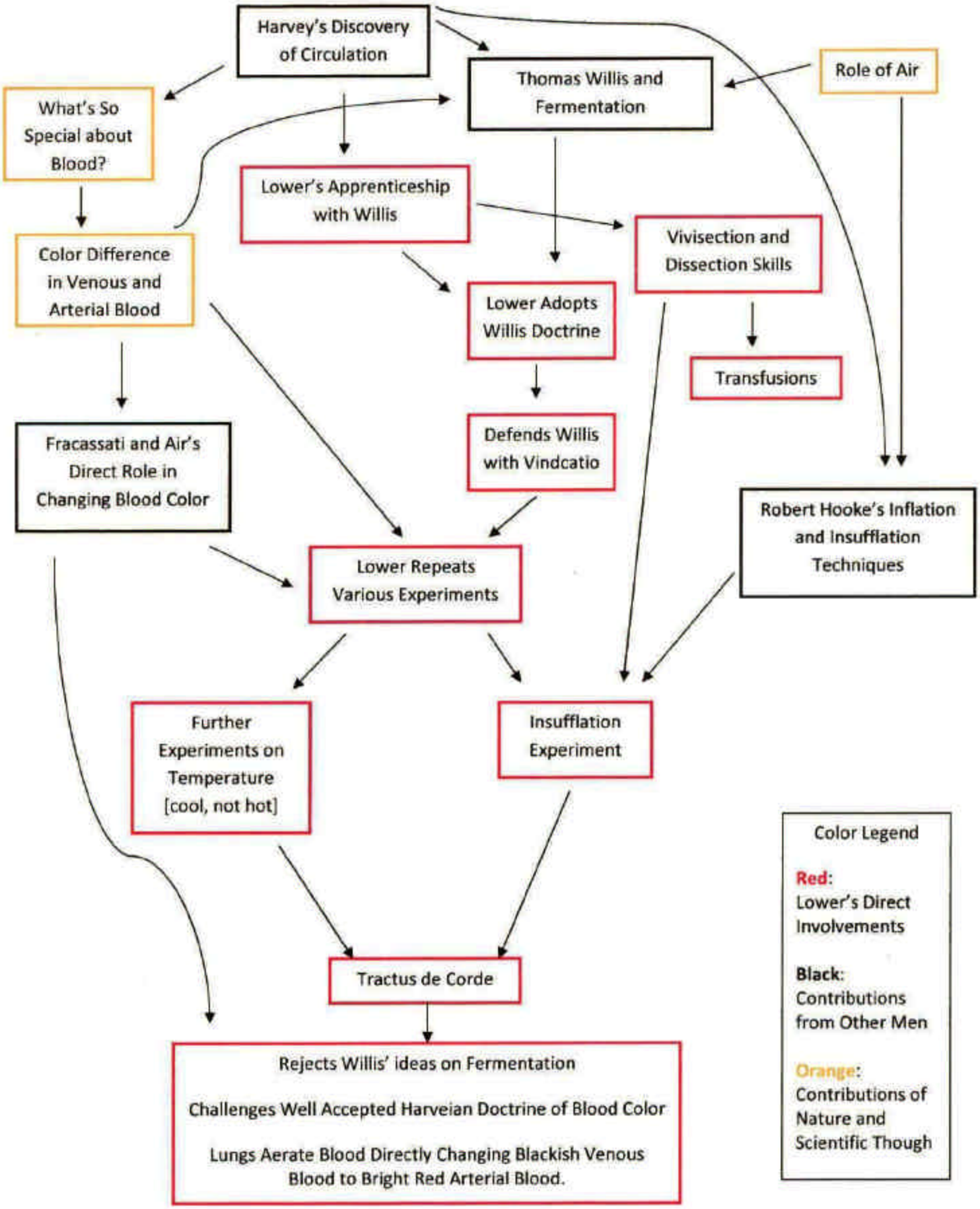
Richard Lower and the "Life Force" of the Body

by Erin Moran

This case study focuses on air's role in creating the bright red color of blood we are so familiar with today. Meant to be taught after an initial introduction to William Harvey and circulation, the module follows the work of Richard Lower, one of the greatest physicians of the 17th century, as he works to explain why blood color in the veins differs from that in the arteries. Through discussion and hands-on activities, the students will place themselves in scientific community at Oxford and think through the same problems and questions faced by Lower himself. Ultimately, the students will discover that fresh air in the lungs provide blood with the "life force" and red hue. Students have to opportunity to also investigate issues relating to:

- Science occurs in personal, cultural and historical contexts.
- Scientists may reach different theoretical interpretations of the same evidence.
- Science is subject to conceptual change.
- Science is a collaborative process.

Narrative Road Map



Richard Lower and the "Life Force" of the Body

by Erin Moran

The Life Force: A Historical Invitation

Life relies on a multitude of microscopic movements of internal organs and processes. Yet, these functions, as small as they may be, are the difference between life and death. The heart beats, the body warms, the lungs expand, the blood flows, the body lives - but how? And more importantly, why? Over the years of the 17th century, scientists across Europe fascinated each other with theories and experiments regarding these physiological phenomena.

William Harvey provided the fervor to explore this area of research in 1628 with his announcement on circulation. He defiantly discarded the Galenic view of two separate vascular systems and replaced it with one of a continuous circulation of blood throughout the body. His use of dissection and vivisection for anatomical discovery would be passed on to his predecessors. Even though Harvey described how blood traveled throughout the veins and arteries of the body, he did little to explain *why*. In the years to come, it will be up to other English intellectuals to finish the masterful work Dr. William Harvey started.

Welcome to Oxford!

The year is 1655. A young graduate from England's Oxford University, Richard Lower, fresh with his Master's degree and medical doctorate is starting a career in a new found mechanical approach to science. Full of energy and a yearning to develop skills with a scalpel, he's searching for a mentor.

Luckily, Oxford at this time is buzzing with scientific activity. Awe and admiration is still circling around the community because of the exciting discovery of blood flow and circulation by the renowned physician and Oxford graduate, Dr. William Harvey. Harvey's close friends and associates are attempting to restore Oxford to its scientific tradition and prestige. During the English Civil War, Oxford surrendered to the Parliamentarians in 1646 and lost most of its top scientists. Now, under new leadership and fresh ideas, the University has attracted many determined, intelligent students.

While accepting his ideas, Harvey's successors are looking to expand upon the central physiological functions of the body using a new atomistic and mechanical philosophy coming out of France. A new science called Chemistry is evolving which examines the

particles and composition of atomic units. Both this concept and a traditional interest in anatomy converge here at Oxford.

In recent years, cooperative research between chemists and physiologists created a group of scientists with a common purpose - to fully understand the function of natural, biological systems using chemical discoveries and anatomical ideas. Everyone is bustling around, sharing ideas and dissections with each other in hopes of discovering a new function or a new explanation.

> **[1]** *Before establishing a medical practice, Lower needs experience working alongside an established physician. Make a list of what you consider key qualities a mentor should possess. What will you expect to learn from them?*

Along with others, Dr. Thomas Willis, a local chemist and physician, helped bring Oxford back to life. On the verge of beginning a practice of his own, he is eagerly welcoming students to assist in progressing his research. Our new graduate fits this position perfectly.

Richard Lower was born into a wealthy household of England. Members of Lower's immediate family belonged to both Parliament and the Cornish gentry. This notable connection, along with his own intelligence led to his acceptance to Westminister School at Oxford in 1649. At Westminister, he received academic honors and rose to King Scholar. Like Willis, Lower aspired to be a physician. With such similar interests in anatomy and physiology, it is no wonder these two men crossed paths at Oxford.

The search for a mentor does not last long for Lower, for he teams up with Willis almost immediately. In the beginning of his apprenticeship, Lower makes frequent house calls to Willis's patients around the country. His emergence as an active practitioner coincides with an increasingly growing interest in anatomy and dissection. Others in the community write about Lower's first dissection. Early notebooks from Oxford detail his first known dissection in 1660, "Mr. Lower cut a doggs windpipe and let him rune about: hee had a week so: he could note smell but would eat anything I was told[1]." Lower lets few dissecting opportunities pass for he is even seen opening the head of a calf at a church one Sunday morning. It was also around this time, Robert Boyle, a fellow scientist, met Lower and the two began collaborating on physiological experiments.

Over the past four years with his apprentice assisting with the treatment of his patients, Willis earns the title of Sedleian Professor of Natural Philosophy at Oxford. Here in the classroom, Willis teaches Lower and other students about the neurological research fascinating him the most. Using the material and concepts learned from Willis, Lower is starting to teach and demonstrate the anatomical functions for others. This new interest in neurology starts a different, more hands on approach to research.

Brains, Hearts and Blood…Oh My!

Inspired by this mechanical approach, Willis begins extensive exploration of the brain with dissections. Taking this cue from his teacher, Lower embraces the art of dissection and fluid injections. For the first time in history, the two men track the speed and course of blood flow through the brain using ink injections. However, the quills being used do not remain firmly inserted in the blood vessels. With this limited access to the vascular system, performing research beyond blood tracking is difficult.

> **[2]** *Before research and dissections can progress further, the medical instruments need modifications. Where do you suggest these adjustments be made? Keep in mind the tool must be both durable and firm.*
>
> **[3]** *With the new tools, in-depth dissections are possible. You must now decide how many and what kinds of animals or specimens to dissect. How do you base your decisions? A lot of the same animal? A few of many? Which animals? How would you benefit from multiple dissections?*

In switching from quills to silver instruments, dissections are becoming a more precise tool for comparative anatomy. Reports recording Lower's anatomical dissections of horses, sheep, calves, goats, hogs, dogs, cats, foxes, hares, geese, turkeys, fishes, monkeys and human cadavers circulate around Oxford.

Based on these numerous dissections from the previous years, Lower is finding himself puzzled by the nature, more specifically, the reason for blood's color. Why does the color of blood in the veins differ from that in the arteries? For ages, stumped scientists questioned this same physiological dilemma. In a letter to Boyle, Lower writes of his intentions to investigate, "the reasons of the different colour of the blood of the veins and arteries; the one being florid and purple red, the other dark and blackish,[1]"

Lower is not the first to make this observation of the differing color between venous and arterial blood. He and the men before him all knew that blood as a single entity flows through the body. Harvey pointed out that blood forms first and dies last in the body. Yet, it appears in the body not as one color but two. Why is this? What role does it play in the function on maintaining life? These questions drive Lower to pursue his own research and scientific theories.

> **[4]** *How would you first approach this problem and with what initial predictions? Imagine 3 experiments to explore further the problem of the difference in blood color.*

[1] Qtd in Frank, Robert "Harvey and the Oxford Physiologists" p. 183-184

Nature of Blood from the Past

Lower will not be working from scratch in the pursuit for answers. Physicians as early as 500 B.C.E. from ancient Greece first observed the variations through the process of bloodletting. The pre-modern scientist Galen claimed the veins and arteries of the body performed completely different and separate functions. Color, therefore, was merely one of the many natural and essential differences in these two systems. William Harvey attributed the coloring to an artifact left over from the strain of the blood leaving the either the narrow arteries or wide veins. Even Lower's own mentor had theories behind the color and motion of blood.

In first half of the 17th century, scientists were suggesting theories on bodily matter contradictory to the natural philosophy of the past. Rather then believing the body had internal "humors" consisting of phlegm, black and yellow bile, and blood, our Oxford scientists put forth a chemical and mechanical theory. According to this theory, the parts of the body separated into five principles based on their composition and activity; spirit, sulphur, salt, water and earth.

Thomas Willis utilized his knowledge of chemistry to connect these ideas with physiological function in 1656. He claimed that through the process of some chemical reaction, an element in the air caused the mixing of these particles. When one principle combined with another from a different class, a change or reorganization occurred. He called this process fermentation. According to Willis, this process could be applied to all fermentable liquids, including blood.

As a heterogeneous liquid, blood consisted of all five elements but most importantly, spirit and sulphur. When left to stand in a bowl, shed blood separates into its parts. Willis explained that blood lost its spirit and nutrients during circulation and therefore sank to the bottom. The florid, still pure blood remained on top. Purification occurred again in the left ventricle, which received all parts of the blood before they entered the body. Here, air combined with particles of the blood, setting it in motion through the rest of the body where it could distribute its nutrients.

> **[5]** *Why does this theory of fermentation seem appealing to Lower and other scientists of the time? How could one provide evidence for this theory and it taking place in the left ventricle?*

However, Descartes proposed an alternative to fermentation and blood which some still held as true. This theory, called ebullition, suggested heat inside the heart boils the blood. The blood then changes shape and swells inside the heart causing the arteries to greatly expand. Movement of the heart is a result of this expansion, therefore making the heartbeat directly dependent on the motion of blood. The passive heart, being analogous to a machine rather than a muscle, relies entirely on the expansion and contraction of the

entering blood for its movement. According to Descartes, an animal remains alive only when blood moves in the heart.

> **[6]** *Already being a strong advocate for this mentor's theory of fermentation, Lower may feel compelled to disprove Descartes in order to support Willis. Describe at least 2 experiments that could test Descartes' theory of ebullition.*

Now having shown that ebullition was not possible, Lower whole heartedly adopted his mentor's ideas on fermentation and the *motion* of blood. Using this theory, it is time for him to further expand on the reasoning and mechanism of blood's color.

Search for the Answers

Like those before him, Lower approaches the color of blood with his own research. After performing a phlebotomy, in which blood is drawn directly from a vein into a collection vessel, he writes to Boyle detailing his observations. Why was it that the collected blood was capped with a layer that "is always florid and finely red, and that under is always dark and black?[2]" Alternatively, he sees that letting blood directly from an artery produces blood entirely bright red and florid.

For further investigation on these phlebotomy effect, Lower injects milk into an animal's artery. He collects the blood from the corresponding vein and observes a milk and blood mixture. To model a phlebotomy, he lets the mixture settle. Milk separates from the blood and sinks to the bottom of the vessel.

> **[7]** *How could Lower use the results from this experiment to explain what happens in the separation of arterial from venous blood? Use the model of this experiment from class to decide which type of blood represents each of the liquids from Lower's test.*

Even with the newly developed injection tools and techniques at his fingertips, Lower continues to opt for Willis' theory of fermentation as an explanation for florid blood. The doors to new research and advancing technology remain closed with the publication of his first work, *Vindicatio* in 1665. In response to criticism from Bristol physician and advocate of Galenic medicine Edmund O'Meara, this book comes to the defense of Willis's work on fermentation of the blood. Page by page, Lower supports the concepts behind fermentation and Harveian circulation.

He goes further to state respiration acts not only to remove wastes but more importantly to provide the 'nitrous food of the air.' Thus, color change in blood was due to the mixing by air of particles in the left ventricle of the heart. Even under scrutiny and

[2] Qtd in Frank, Robert "Harvey and the Oxford Physiologists" p. 184

criticism from others, Lower never wavers but continues to remain to the teachings of his mentor.

Where did this 'nitrous food of air' come from?

While Lower informed Boyle about his work with blood during his time at Oxford, Boyle responded with details on the physiological work of his own. In London, Boyle concerned himself with the role of air and respiration. Since 1660, Boyle and his partner Robert Hooke conducted numerous experiments with air. They created the air pump in order to explore the components of air and how they changed in a vacuum.

Work with the air pump led Robert Hooke, who also started as an assistant of Thomas Willis in the laboratories of Oxford, to the physiology of respiration. As fermentation and other circulatory theories suggested, arterial blood picked up 'something' from the air coloring it a bright red. He noticed that when placed in the air pump, fresh lamb's blood frothed as the pressure inside decreased. When testing venous blood in the same manner, nothing happened. This evidence led Hooke to suggest in 1664 that perhaps this vital air mixed with blood inside the lungs, not the heart. Now, Hooke must decide if the motion of the lungs themselves or the passage of air in the lungs sustained life.

> **[8]** *Hooke must devise an experiment to test his ideas. Suggest an experiment Hooke could use. Which variables are being tested? Which ones are controlled? What would be important to measure or observe?*

In front of an audience of his colleagues, Hooke conducts the following experiment. By attaching a pair of bellows to the trachea of a living dog and cutting away the thorax and diaphragm to observe the heart, he shows the motion of the heart is only maintained when the bellows inflate the lungs. The lungs lose their firmness and the heart convulses when one removes the bellows. When the motion of the bellows restarts, the lungs inflate and the convulsions cease. This inflation experiment showed air, not the motion of either the heart or lungs, was the life force of animals. Although he found answers to his question, Hooke is disturbed by the procedure however. Several of his colleagues encourage him to pursue these experiments further but Hooke claims he could, "hardly be induced to make any further trials of this kind, because of the torture to the creature.[3]"

Inflation to Insufflation

The summer of 1665 descends upon the community accompanied with a standstill in the advancing research of blood, respiration and circulation. Plague and a great fire strike down on London, making communication between scientific communities of London and Oxford exceedingly difficult. Lower pursues his own interests both professionally and personally. In 1667, with his new wife in tow, Lower follows Willis to London. There, he establishes his own medical practice and reunites with many of the most active

[3] Qtd in Frank, Robert "Harvey and the Oxford Physiologists" p. 158

members of Oxford. With his professional career growing, Lower resumes his anatomical research in his new city.

Boyle and Hooke, also in London at the time, introduce Lower to the open thorax experiment from 1664. Hooke reveals also his belief that with certain modifications, this procedure could provide further proof that it is the quality of air which keeps animals alive. This modification requires making an incision in the lungs to allow air to continually pass over them. Because of his distaste for the vivisection procedure, Hooke recruits Lower and his expert hand to help. The men perform the vivisection in the spring of 1667, just seven days after Lower becomes a member of another community of scientists called the Royal Society.

Lower repeats the 1664 experiment with Hooke but this time, they introduce a second set of bellows to enable a continuous stream of air over the lungs. The dog remains alive with its lungs full of air even though the lungs stay motionless. Lower slices a piece of lung and sees blood always flows freely through the lung, even when lying still. The team of men prove once again that "the bare Motion of the Lungs without fresh Air contributes nothing to the life of the Animal[4]," and death could not be caused by "the stopping of Circulation of the Blood through the Lungs, but the want of a sufficient supply of fresh air,[5]". While Hooke is left with more questions to answer about the role of respiration, Lower continues to show his skill with the scalpel in multiple physiological experiments including the first animal and human blood transfusions in England.

> **[9]** *Hooke and Lower proved the necessity of air in the circulation of blood and life. Now the question remains if air adds something to the blood or takes something away. Suggest what observations in the body are necessary to give further insight of the effects of air on the blood.*

Blood Work across the English Channel

At the same time across Europe, Italian doctor Carlo Fracassati is doing work of his own with injection experiments and the nature of blood. He is observing the effects of injecting various chemicals into dogs. These injections enable him to conclude that death sometimes results from the coagulation of blood. Like Lower, his work with injections leads Fracassati to the mystery of blood color.

Fracassati maintains his own views on the color of blood according to his observations. While others "vulgarly maintained" the bottom, dark layer of cooled blood left to stand in a bowl was a result of its composition of humors or "melancholy", he believed otherwise. He held that, "the blackish colour comes from hence, that the bloud, which is underneath

[4] Qtd in Hooke, Robert "An Account of an Experiment made by Mr. Hook…" p. 539
[5] Qtd in Hooke, Robert "An Account of an Experiment made by Mr. Hook…" p. 539

is not expos'd to the Air, and not from a mixture of Melancholy,[6]". In order to see this effect, one would only need to expose the dark portion to air and it would become more florid and red.

News of Fracassati's elegant experiment traveled from Italy to London via another scientific collaborator and secretary to the Royal Society, Henry Oldenburg. As a close friend of Boyle, Oldenburg knew he would be interested in these findings. Boyle replicated the experiment himself and produced the same results. The Royal Society's journal, *Philosophical Transactions* publish the details of the Fracassati experiment for the rest of the scientific community to read. This journal recorded the work and observations of the Royal Society members and associates.

> **[10]** *What is the difference between Fracassati and Lower's views on blood color? Since criticism often lead scientists to reassess or reexamine their own ideas and theories, how do you react to these observations of blood color if you were Richard Lower? What experiments are necessary to test Fracassati's claims? How would you adjust your initial experiment of milk and blood?*

This Italian with his simple experiment challenges all of Lower's work up to this point in his career. Men since Harvey always held with explicit faith that something produced during the process of fermentation entered the blood during respiration and caused a color change. Lower wrote of these personal beliefs both to Boyle in 1664 and throughout *Vindicatio* in 1665. Now, he comes face to face with the convincing evidence that direct contact of air itself gives blood its florid color.

Upon reading this edition of the *Philosophical Transactions*, Hooke quickly devises an experiment integrating both Fracassati's results with his own insufflation technique. He writes to the Royal Society in 1668 that it would be worthwhile to observe the color of blood both before and after it passes through the lungs. These results may once and for all indicate if it is the mixing of air and blood in the lungs which produces the bright red color.

Lower's Retort

In the meantime, Lower decides to discontinue all anatomical activity with the Royal Society between 1668 and early 1669. However, he is still continuing with his own private research and growing medical practice. Because of Lower disappearance from the public science limelight, Hooke is unable to share the details of his new procedure. Since the experiment relies on Lower's vivisection skill, Hooke is never able to carry it out alone.

[6] Qtd in Fracassati, Carlo "An Experiment of Signoir Fracassati…" p. 492

Although Lower neither attends or contributes to Royal Society meetings, he does not stop investigating the now even more puzzling problem of blood color. With a different perspective and challenge to both his mentor and own ideas, he sets out to find his own evidence for Fracassati's results.

Hooke never possessed the skill or vivisection knowledge to execute the insufflation experiment accompanied with his new ideas on the role of the lungs in changing blood color. Lower, with the ideas of both Hooke and Fracassati and his own vivisections skills so well honed through the years of his apprentice, performs this crucial experiment.

In the open thorax procedure, Lower exposes the trachea of a dog and inserts a cork to prevent the flow of air into the throat. He observes that blood contained in the cervical artery of the neck appears dark and black like blood found in veins. He cuts open the pulmonary vein and finds blood. Removing the top part of blood and thus exposing it to air, causes the underlying venous blood to turn bright red.

In a second experiment, Lower lets the dog die. Then, using a pair of bellows, inflates the lungs while simultaneously injecting them with venous blood. Upon discharge, the blood appears bright red.

> **[11]** *What has this one experiment revealed to Lower about the nature of blood color? In the first experiment, what conclusion can be drawn about the role of air? What does the second experiment say about the role of heat? How has his theories changed from Vindicatio? What would you recommend he do with these findings?*

Lower complies the results of the open thorax experiment in his book, *Tractus de Corde* of 1669. The publication of this work gives him the opportunity to publicly correct the errors made in *Vindicatio.* He confesses that he, "relied more in this matter on authority and preconceived opinion of the learned Dr. Willis than on my own experience, and confused too far the torch of life with its torch-bearer[7]".

> **[12]** *What personal and professional qualities does this comment reveal about* Lower? *Why do you think this is an important aside to make? Would you have said the same about your mentor even when proving him wrong?*

The first half of the book describes the structure and function of the heart. Lower points out that in order to fully understand the nature of the blood, one must first understand the surroundings in which it worked. He makes his argument on the color of blood. The color of venous and arterial blood is independent of fermentation or heat in the heart. He "drove on the blood, and carried out a simultaneous insufflation of the perforated lungs[8]."

[7] Qtd in Gunther, R.T. "Early Science in Oxford: De Corde By Richard Lower" p. 7
[8] Qtd in Gunther, R.T. "Early Science in Oxford: De Corde By Richard Lower" p. 165

of a strangled dog. The results from this experiment reveal "the blood was discharged into the dish as bright-red in colour, as if it were being withdrawn from an artery of a living animal[9]." Therefore, heat of a live animal is not required nor responsible for the color of blood.

Also, the bright red and florid arterial blood is due only to the direct contact of fresh air in the lungs. Lower writes about the variety of experiments conveying this idea. He again continuously inflates the lungs with the bellows and exposes the traecha. If then the small punctures in the traecha allow free passage of air, "on the pulmonary vein being cut near the left auricle, the blood will flow out into a suitably placed receptacle completely bright-red in color.[10]" He echoes Fracassati's experiment and the separation of blood in a phlebotomy experiment as further evidence of air's interaction with blood. Lower explains that after blood separates and the top layer of blood removed, the underlying dark layer will change to bright red upon exposure to the air.

With each experiment Lower describes, the relationship between blood and air becomes clear. Air comes in to the body during respiration whereupon it mixes with the dark blood entering the lungs. The blood leaves the lungs bright red after having taken in the air and continues circulating through the rest of the body. In a book of little over 200 pages, Richard Lower not only rejects his mentor's beliefs on fermentation but challenges the honorable Harveian system. The heart is indeed a muscle as Harvey and Willis claimed but it's motion did not cause an internal heating source. Nor is this heat the reason for the difference between arterial and venous blood.

> **[13]** *Throughout his research and discovery, Lower surrendered many preconceptions that coincided with the historical perspectives of this time. What concepts was he force to think* ***through*** *in order to reach this final conclusion? How do you think challenging such traditional idea feels?*

There is no doubt that Lower had the intelligence and drive to pursue such a complex problem. While Lower receives full credit for "discovering" the answers to this long standing physiological question, he could not have done so without the help of the scientific community in which he belonged. Thomas Willis gave him the resources and opportunities to sharpen his dissection and vivisection skills in a research environment. Robert Boyle's work on the air pump and respiration gave insight to the role of air in life. The inflation and insufflation techniques developed by Robert Hooke provided tools to explore the problem of blood further. Carlo Fracassati then gave Lower the final piece of the puzzle by observing venous blood exposed to air would become florid. Although it was the contributions of all these men that lead to the final conclusion, only Lower successfully pieced it all together.

[9] Qtd in Gunther, R.T. "Early Science in Ocford: De Corde By Richard Lower" p. 166
[10] Qtd in Gunther, R.T. "Early Science in Oxford: De Corde By Richard Lower" p. 167

Images

1. Richard Lower. This is the only known painting of Lower. From “Early Science in Oxford: De Corde by Richard Lower.”

2. Map of Narrative. This roadmap summarizes the ideas woven throughout the narrative. Can be used as notes and reference while teaching.

3. Heart. Lower’s sketch of the heart published in *Tractus de Corde.* Meant to highlight the tendons and fleshy fibers of the heart proving it is a muscle. Evidence against Descartes’ theory of ebullition. From “Early Science in Oxford: De Corde by Richard Lower.”

4. Injection Tools. Drawings of injection tools used by Lower as seen in *Tractus de Corde*
Fig 1. Simple Silver Tube
Fig 2. Convey Blood to Human Arm
Fig 3. Tubes for Blood Transfusion
Fig 4. Cervical Artery (a) Fitted to a Silver Tube
Fig 5. Apparatus for the Transfusion of Blood from One Animal to Another
Fig 6. Apparatus for the Transfusion of Blood from an Animal to Man
From “Early Science in Oxford: De Corde by Richard Lower.”

5. Evolution of Tools. Outlines pictorially the progression of transfusion and injection tools used by Lower. From “Richard Lower: Anatomist and Physiologist”

References

Felts, John H., MD. “Richard Lower: Anatomist and Physiologist.” *Annals of Internal Medicine* 132.5 (2000): 420.

Fracassati, Carlo. “An Experiment of Signior Fracassati upon Bloud Grown Cold.” *Philosophical Transactions* 2(1666): 492.

Frank, Robert Gregg. *Harvey and the Oxford Physiologists : Scientific Ideas and Social Interaction*. Berkeley: University of California Press, 1980.

Gunther, R.T. *Early Science in Oxford: De Corde By Richard Lower.* Great Britain: Oxford University, 1932.

Hooke, Robert. “An Account of an Experiment made by Mr. Hook, of Preserving Animals Alive by Blowing through their Lungs with Bellows.” *Philosophical Transactions* 2(1666): 539-40.

Lower, Richard. *Vindicatio*. Ed. Kenneth Dewhurst. Oxford: Sansford Publications, 1665.

“Lower, Richard.” *Dictionary of Scientific Biography*. Charles C. Gillispie, ed. New York: Charles Scribner's Sons, 1973. 523-527.

R^d Lower

Tab. 5

Fig 1

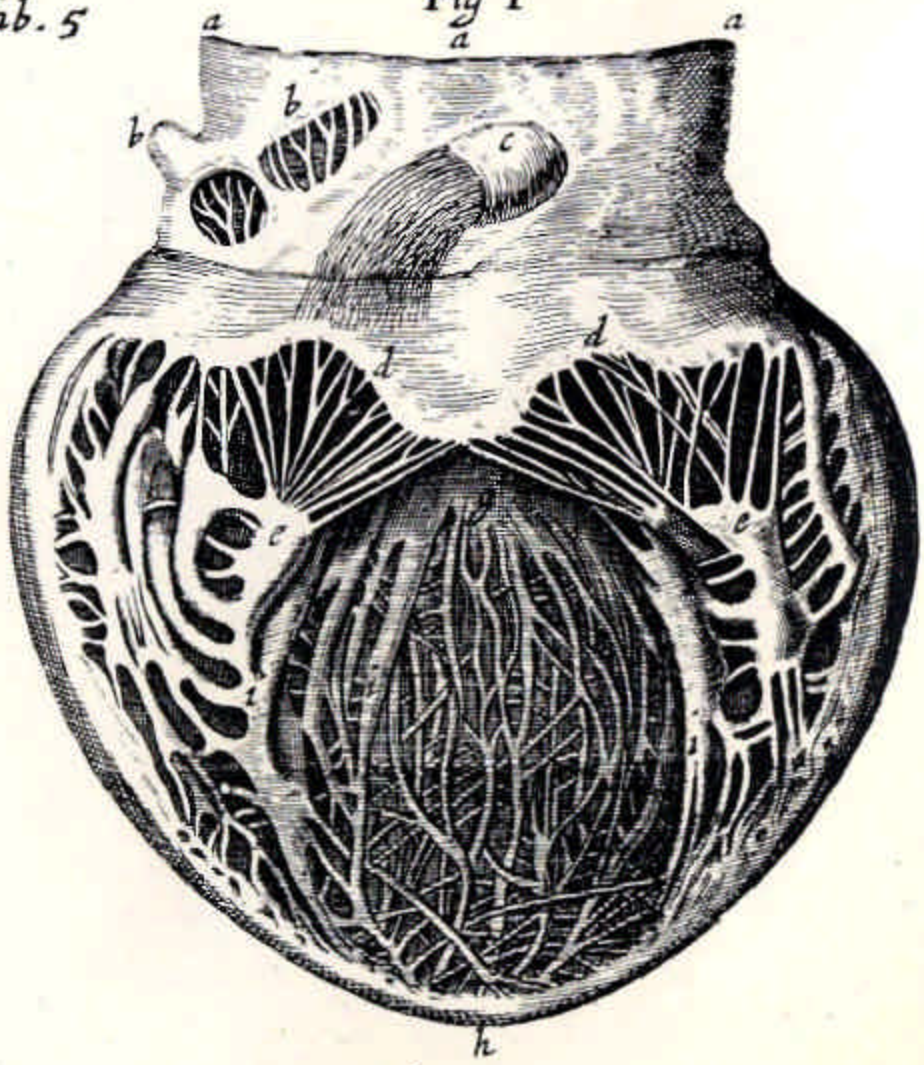
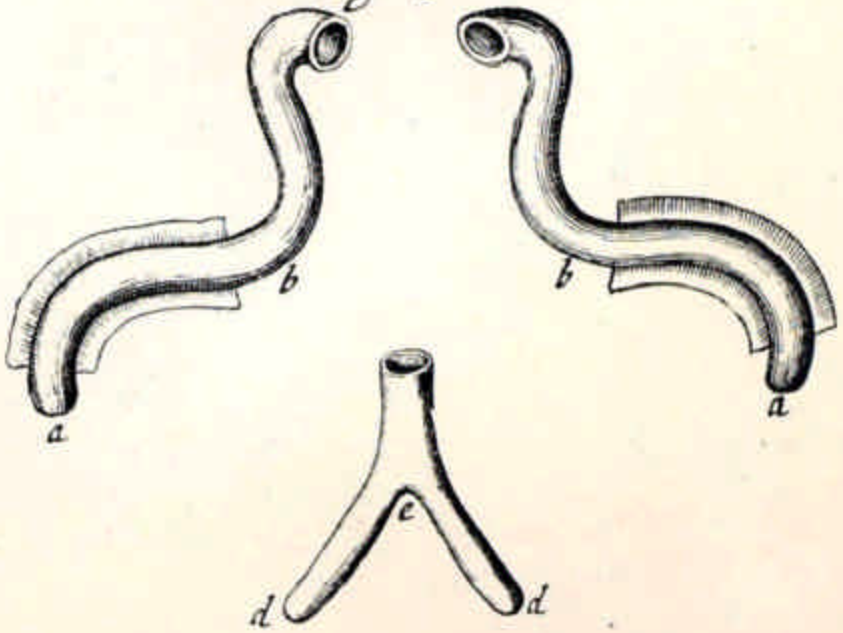


Fig 3



Tab. 7.

Fig. 1.

Fig. 2.

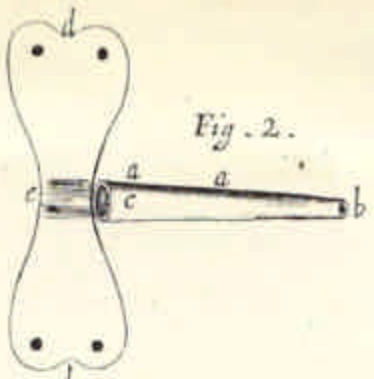


Fig. 3.

Fig. 4.

Fig. 5.

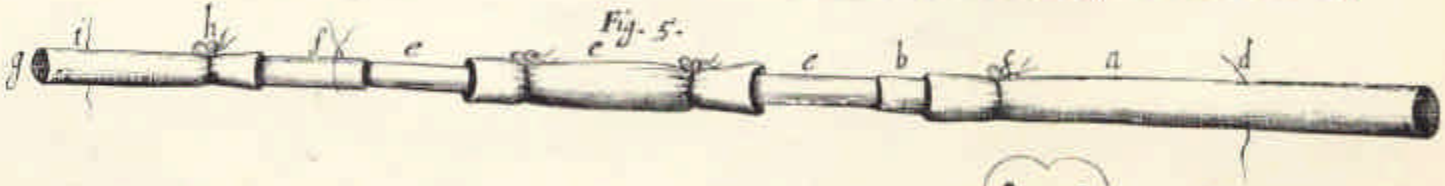
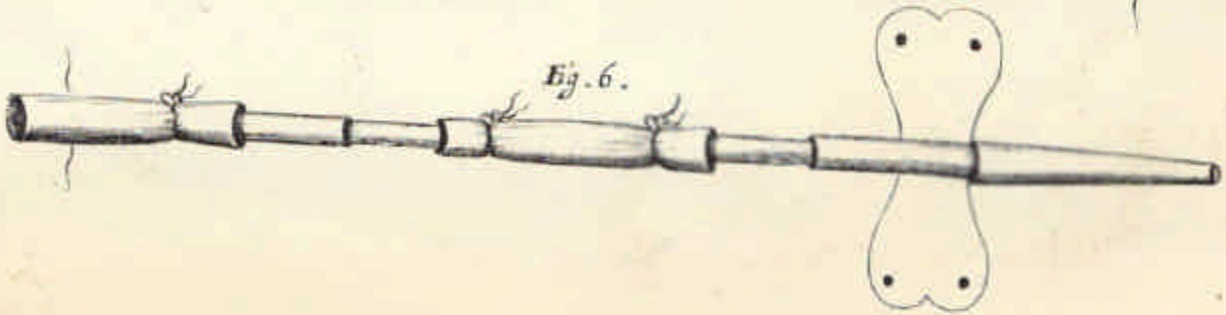
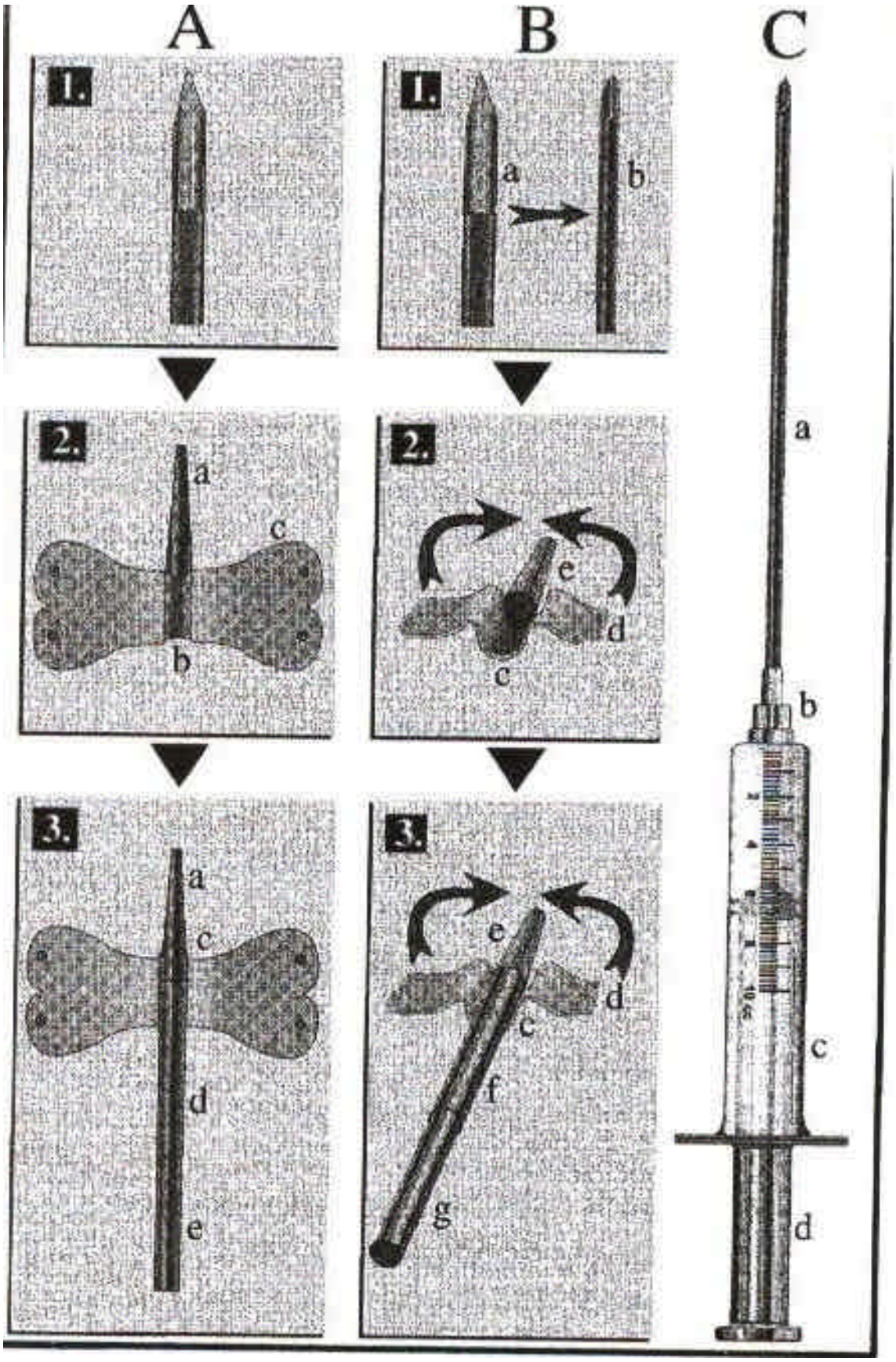


Fig. 6.




A
B
C
1.
1.
a
b
2.
2.
a
c
b
e
d
c
3.
3.
a
c
d
e
e
d
c
f
g
a
b
c
d

Teacher's Notes and Supplemental Questions

[1] What are the qualities of a good mentor?
The students will imagine themselves as Richard Lower in search of a mentor. Either in small groups or as a class, discuss the qualities and characteristics Lower would want to find in a future teacher.

After introducing Thomas Willis as Lower's mentor, students can decide whether or not they think Willis possesses the qualities they considered important.

Discussion Questions:
Before establishing a medical practice, Lower needs experience working alongside an established physician. Make a list of what you consider key qualities a mentor should exhibit. What will you expect Lower to learn from his apprenticeship ?

[2]/[3] Evolution of Surgical Tools Lab
This lab allows the students to hypothesize and investigate how to improve the equipment. They will use different materials in order to decide which is best for the experiments Lower was to attempt.

Materials:
- Balloon
- Scalpels of various blade sharpness
- Large Bowl

On each of the scalpels, place labels of various possible materials for the tools including quills, iron and silver. The sharpest scalpel should be labeled "silver." Stretch a balloon over the bowl. Students will use the "tools" to decided which strength would be tough enough to cut through and remain embedded in the "skin." After experimenting, explain how as a flexible yet sturdy metal, silver was ideal for blood vessel experiments. Include the images showing the evolution of Lower's tools into the modern syringe.

Discuss how the new tools lead to new types of dissections. Allow the students to reason why it may be more beneficial to make multiple observations of various animals in order to get a complete view of the problem.

[4] Initial Approaches to the Problem
These questions allow the students to think about how Lower first approaches experimenting with blood color. Let the students exchange ideas with each other on what types of tests are needed to give Lower more information on the color of blood. In working with other classmates, you can demonstrate how science, especially like at Oxford, often involves collaboration with peers.

Students can break into small groups in order to brainstorm ideas based on the circulation of the blood according to Harvey and what the students already know about the color. In a large group discussion, share all the ideas and decide which ones could be tested during the 17th century.

[5] Fermentation

Allow the students to discuss why fermentation seemed like a reasonable suggestion for the time. Willis' studies focused heavily on chemical processes and therefore it would seem appropriate for him to suggest these ideas considering his background in chemistry. Furthermore, at the time of mechanical science, scientists searched for alternatives to the natural philosophy previously used. Therefore, dividing the blood and bodily matter into particles based on their chemical composition rather than the "humors" would be readily accepted.

Willis further disproved the natural philosophy of blood composition by showing through distillation that blood cannot be separated into its separate, internal humors. On the other hand, blood did indeed separate based on its chemical properties. Observation of red, florid blood in only the left ventricle became his evidence for the location of fermentation.

[6] Ebullition

Descartes proposed theories on ebullition in which the blood essentially boils in the vessels of the heart. This boiling causes the arteries and veins to expand resulting in a heartbeat. He also believed the heat produced maintains life and an animal would cease to exist without this process.

Lower performed numerous experiments that disproved the theory of ebullition. Students can think about what kinds of tests could give evidence that would show error in Descartes reasoning. After discussing their ideas, further suggest the others Lower did indeed conduct and conclusions he drew as listed below:

Dissection of the heart (Use image of heart)
- -Reveals fibrous tissues similar to that of a *muscle*
- -No place suitable or large enough for ebullition to occur

Heart removed from a living animal and completely drain still continues to move
Replaced blood of a dog with liquor wherefore the heart still beat for sometime
One does not feel a heat of such intensity when touching the heart during a vivisection
Recording the time for circulation shows the blood does not remain in the heart long enough for such a reaction to occur

[7] Blood is Thicker than Water…and Milk Lab
Demonstration of Lower's initial experiment

Materials:
Vegetable Oil
Milk
Glass Jar w/ lid

Combine the vegetable oil representing blood and milk in the jar. With lid on, mix the liquids together. Showing that upon settling, they layer out. This resembles the experiment done by Lower explaining how arterial blood separates from venous blood. Lower believes venous blood separates itself from arterial blood in the same way because it contains less 'spirit' making it heavier and more dense. The more spirituous arterial blood on the other hand floats to the top.

[8] More on the Experimental and Research Process: Testing a "Hypothesis"
This set of questions should lead students to the open thorax procedure Hooke devised. The students should create a list of experiments that aims to test one of the variables Hooke contemplates as being responsible for altering blood color - either the motion of the lungs or motion of the air in the lungs. Encourage them to explain which method would be easiest to examine and then introduce Hooke's plan on the open thorax procedure.

[9] How to Expand on Hooke and Lower's discovery
Determine if the students understand what the inflation experiment proved and discuss what further work is needed. After hearing their ideas, introduce Hooke's suggestion to perform a lung bypass. Explain how observing the blood before and after it enters the heart will provide convincing evidence that air does cause the bright red color of blood.

[10] Differences in Opinions
Discuss first the student's thoughts on the differences between Fracassati and Lower's views and ideas on how to test Fracassati's claims.

Then, with the students, make a list of the various opinions and explanations on the color of blood up to this point in the narrative. Show and discuss how both historical and scientific context of each time period can influence scientific discovery. Discuss how it is not uncommon for scientists to have various theories on the same subject and how it is often these differing views lead to a better explanation.

[11] Lower's "Experimentus Crucius"
Either small group or class discussion on what evidence Lower revealed in his experiments. Let the students identify how Lower has modified his view since the publication of *Vindicatio.* Ask whether they would publish these new findings, knowing they completely contradict that of their mentor and friend.

[12] Science and Respect Among Peers
Opportunity to briefly discuss how scientists tend to show respect to work done before them. This is an important quality in modern scientific research papers and scientists. It also demonstrates the collaborative characteristic of science.

> Discussion Questions:
> *What personal and professional qualities does this comment reveal about* Lower? *Why do you think this is an important aside to make? Would you have said the same about your mentor even when proving him wrong?*

[13] Challenging a Tradition
This allows the students to express how they would feel if put in Lower's position considering he not only challenged an accepted belief but also disagreed with a mentor.

Final Discussion

Timeline of Research Project
Lower took one man's profound discovery and completely altered it. Review the process once again with the students that Lower went through to get to his final conclusion. As an end project, students can construct a timeline of events important to his discovery. Making sure to add that time lines can be constructed either chronologically or according to key experiments. Students must explain why they chose the method they do.

Animal Ethics in Research
As a concluding discussion, address how animal ethics now is an important part of scientific research. Introduce students to the three R's of animal ethics. Reduction, Refinement and Replacement.

> Discussion Questions:
> *Does it seem as though animal ethics were a concern at all during this time? How do you feel about the range of animals that were used in the dissections? What could Lower and his colleagues done differently to consider the well being of animals?*