Freshman Laboratory schedule (2024–25)*

Observing Living Beings

1. Reading: Theophrastus, *An Inquiry Concerning Plants*, Book I, chapters i–ii.

   Practicum: Observe and discuss magnolias in courtyard (shape of whole, branching patterns, leaves, buds). Take notes and make drawings. Prepare seeds for practicum on days 3 and 4.

2. Reading: Theophrastus, I, chapters iii–iv.

   Practicum: Examine magnolia buds (two kinds), stems, leaves, etc. Further examination using dissecting tools, magnifying glasses, dissecting scopes. Notes and drawings. OR

   Practicum: Look at some of the other trees on campus or continue looking at magnolias.

3. Reading: Goethe, *Metamorphosis of Plants,*† poem, Goethe's introduction, sections I–VII.

   Practicum: Seed, seedling, and flower observation. Notes and drawings.

4. Reading: Goethe, sections VIII–XVIII.

   Practicum: Seed, seedling, and flower observation continued. Notes and drawings.

5. Reading: Aristotle, *Parts of Animals*, Book I, chapters 1, 5.

   Practicum: Collect fish from College Creek to put in tanks. Make observations from shore.

6. Reading: Aristotle, selections, *On the Movement of Animals*, *On the Gait of Animals*.

   Practicum: Observe fish in tanks. Include invertebrates such as sea-urchins, if possible.

7. Reading: Aristotle, *Parts of Animals*, Book II, chapters 1, 2.

   Practicum I: Observe external anatomy of fish. Notes and drawings.

8. Practicum II: Observe internal anatomy of fish. Dissection. Notes and drawings. Start discussions of the practicum.

9. Reading: Aristotle, *Parts of Animals*, Book II, chapters 4, 8–12; Book III, chapters 4–6.

   Practicum: Continue discussions of the practicum.

10. Reading: Aristotle, *On the Soul*, Book II, chapters 1–4. [and 12]

11. Reading: Galen, *On the Usefulness of the Parts of the Body*, IV.1–6 and VI.2.

    [Some classes may read both Galen readings on day 11, to reserve day 12 for Harvey. There is also a set of helpful notes on Galen.]

    Practicum: Observation and dissection of sheep pluck. Notes and drawings.

12. Reading: Galen, *On the Natural Faculties*, III.15. Harvey, *On the Movement of the Heart*,‡ Letter to Dr. Argent, chapters 1–7.

    Practicum: Observation and dissection of cow heart. Notes and drawings.

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*This schedule is not divided by semester. But there are 58 entries, of which 7 are optional; and roughly 30 classes each semester. This suggests getting through about four days of the M&E segment by the end of first semester.

†MIT edition preferred.

‡Resource edition preferred.

13. Reading: Harvey, chapters 8–14.

    Practicum: Observation of chick embryos.

14. Reading: Harvey, chapters 15–17, Letter to King Charles I.

    Movie: "William Harvey and the circulation of the blood" (40 minutes—either in class or in FSK/Hodson Room). Discussion of observations and dissections.

15. Reading: Virchow, two lectures from *Cellular Pathology*.

    Practicum: Microscopic examination of different types of cells, prepared slides and fresh (onion, carrot, etc.). Notes and drawings.

16. Reading: Portmann, "The Whole and Its Parts: The Problem of Cell Formation and Organization." AND/OR

    Reading: Shapiro, "Bacteria as Multi-Cellular Organisms." (not in manual)

    Practicum: Cell observation continued, unicellular organisms. AND/OR

    Practicum: Observation of volvox algae.

17. Reading: Driesch, *The Science and Philosophy of the Organism*, pages 1–33.

    Practicum: Sea urchin fertilization and early development; notes and drawings. Observing fertilization and its immediate effect on the egg can be done at the beginning of the class. After discussing the reading, students can return to the microscopes, late in the class, to observe early cleavage.

18. Reading: Driesch, pages 34–58. (OR 34–47, 52–55)

    Practicum: Sea urchin gastrula and pluteus; notes and drawings.

19. Reading: Driesch, pages 59–84. (Can be skipped if needed.)

    Sea Urchin Videos (optional).*

20. Reading: Driesch, pages 85–109.

    Practicum: Begin planaria experiment, observation and initial cutting. (Distribute "Student Surgery Sheet"—not in manual—with pictures of expected results deleted.)

21. Reading: Spemann "The Organizer-Effect in Embryonic Development." (Nobel lecture)

    Practicum: Continued observation and experimentation with planaria.

22. Reading: Spemann, *Embryonic Development and Induction*, chapters XVII, XVIII.

    Practicum: Planaria concluded.

23. Reading: Straus, "The Upright Posture."

    Practicum: Experiment with various gaits, etc.

24. Reading: Jonas, "Biological Foundations of Individuality." (optional) OR

    Reading: Aristotle, *On the Soul*, II.1-4. (optional—repeats day 10) ■

*There is also a memorable "Frog Film" (about 30 minutes long), set to music from *The Rite of Spring*, that used to shown around the second day of Spemann.

Measurement and Equilibrium*

1. Reading: Aristotle, selections, *Categories*.

   Practicum: Observing inanimate objects: collection of rocks and minerals.

2. Reading: "The Question of Measurement." "Ordinal, Interval, and Ratio Scales."†

   Practicum: Exercise 1, "Measurement of a length and a width."

3. Reading: Aristotle, *On the Heavens*, Book IV, chapters 1, 3–5. (optional, not in manual)

4. Reading: "Measuring Weight."

   Practicum: Exercises 2–9 (These time-consuming exercises may be abbreviated by, for instance, limiting the subdivision of the *baros*.)

5. Reading: Archimedes, *On the Equilibrium of Planes*, Postulates, Propositions 1–7.

   "Center of Weight" (paragraph at beginning of chapter II).

   Practicum: Exercises 1–3, "Center of Weight."

6. Reading: Archimedes, *Planes*, Props. 8–10 (read enunciations of the rest).

   Practicum: Exercises 4–5, "Cases of Equilibrium," "The Law of the Lever." (Short practicum.)

7. Reading: "Turning Power." "Pulls."

   Practicum: Exercise 6 and Exhibit 7, "Newton's Wheel." Problems, Chapter II.

8. Reading: Archimedes, *On Floating Bodies*, Postulate and Propositions 1–4, enunciation of 5.‡

   Practicum: Exercise 1, "Buoyancy of Floating Bodies." (Short practicum.)

9. Reading: Archimedes, *Floating Bodies*, Propositions 5–7. "Buoyancy." "Density."

   Practicum: Exercise 2, "Buoyancy of Sinking Bodies." (Short practicum.)

   Practicum: *Alternative*: "The Crown Problem" and Exercise 3, "The Crown Problem."§

10. Reading: Pascal, *A Treatise on the Equilibrium of Liquids*, Chapters I–III.

    Practicum: Exhibit 4, "Equilibrium of a Single Fluid." Also machine for multiplying forces (two syringes connected by a tube of fluid).

11. Reading: Pascal, *Liquids*, Chapters IV–VII.

    Practicum: Exhibit 5, "Equilibrium of Two Fluids." Problems, Chapter III.

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*The practica in the manual for this segment (and the next) usually appear in separate sections after the readings. The problems for all chapters appear in the appendix.

†This reading is indebted to a 1946 article in *Science* by S. S. Stevens: "On the Theory of Scales of Measurement."

‡Proposition 5 is needed for Exercise 1.

§There is disagreement about whether the Crown Problem is worth doing. Some tutors have read Vitruvius or Galileo instead of the manual on the problem.

12. Reading: Pascal, *Treatise on the Weight of Air*, Chapters I, II.
    Practicum:[a]
    (a) Weigh a balloon with and without air. (Chapter I, paragraph 1)
    (b) Seal a syringe and try to open it. (II.I)
    (c) Try to pry apart two glass surfaces or suspend them in air. (II.II)
    (d) Straws. (II.III)
    (e) Rarify vessel of air with candle to make water rise up in inverted glass. (II.III)
    (f) Invert a glass of water in a tub of water. (II.IV)
    (g) Make a siphon. (II.V)

    [a] Roman numerals after (12b)–(12g) above refer to locations of the experiment in the *Treatise* by chapter and section.

13. Reading: Pascal, *Air*, Chapters III–VI; Conclusion; Perier's letter and experiment, Pascal's comment.

    Practicum: Exercise 1, "Construction of a Barometer." In place of a mercury barometer, make a water barometer in the pendulum pit. Exercise 2: "The Experiment of Perier." Instead of constructing barometers, read barometers installed at the Boathouse and in the McDowell cupola; bring semi-inflated taped balloons. The Cartesian diver. Exhibit 3: "The Constant Flow Reservoir."

14. Same assignment as day 13.

15. Reading: Mariotte, *Relations of Pressure and Volume of Air*. "Pressure and Volume."

    Practicum: Exercise 4, "Air is condensed. . . ." Problems, Chapter IV.

16. Reading: "Sensible Heat." Fahrenheit, "The Fahrenheit Scale."

    Aristotle, *Parts of Animals*, II.2, 648a20–649b7. (optional, from *Observing Living Beings*)

    Practicum: Exercise 1, "The Unmarked Mercury Thermometer." Exercise 2, "The Celsius Scale." Exercise 3, "The Temperature of a Mixture."

17. Reading: Black, Extracts from *Lectures on the Elements of Chemistry*, "Equilibrium of Heat," "Specific Heat." Reread "Ordinal, Interval, and Ratio Scales" and Exercise 1, "Measurement of a Length and a Width," in Chapter 1 of manual.

    Practicum: Exercise 4, "The Specific Heat Capacity of Aluminum."

18. Reading: Black, Extracts, "Latent Heat," "Of Vapor and Vaporization." "The Unit of Heat."

    "Variability of Specific Heat Capacities with Temperature." "Scales of Measurement for Warmth and Heat." (optional readings)

    Practicum: Exhibit or Exercise, Supercooling (not in manual). (Short practicum.)

    Problems, Chapter V

19. Reading: Gay-Lussac, "Investigations on the Expansion of Gases and Vapors." "The Absolute Scale of Temperature." "Determination of Absolute Zero." "Is Heat a Euclidean Magnitude?"

    Practicum: Exercise 1, "The Expansion of Gases by Heat." Problems, Chapter VI.

20. Reading: Aristotle, selections, *Categories* (optional—repeats day 1). OR

    Reading: ____, *On Generation and Corruption*, II.[1–2], 3–4, 8. (optional—not in manual) ■

Constitution of Bodies

1. Reading: Lavoisier, Preface (Dover) or Preliminary Discourse (Green Lion).*
   Practicum: Exhibit: "butters," "oils," "flowers."
2. Reading: Lavoisier, Chapters I and II
   Practicum: Boiling water at room temperature in a vacuum. (optional, not in the manual)
3. Reading: Lavoisier, Chapters III and IV. "Use of the Chemistry Laboratories."
   Practicum: Exhibit: Oxidation of rusting iron. Experiments: Acids and alkalies.
4. Reading: Lavoisier, Chapters V and VI
   Practicum: Experiments: Metals and nonmetal oxides.
5. Reading: Lavoisier, Chapters VII and VIII
   Practicum: Exhibit: Action of "fixed air" on green leaves. Exhibit: Liberation of hydrogen from water vapor.
6. Reading: Lavoisier, Chapters XVI and XVII. "Remarks on Muriatic Acid."
   Practicum: Exhibits: 1–4 (in connection with Lavoisier's Chapter XVI).
   Practicum: Experiments: Reactions of metals with water and acids.
7. Reading: Dalton, Extracts from *A New System of Chemical Philosophy*.
   Reading: Thomson, Extracts from *System of Chemistry*. Appendix 2: Berthollet and Proust.
   Practicum: Experiment: Multiple combining proportions.†
8. Reading: Gay-Lussac, "Memoir on the Combination of Gaseous Substances with Each Other."
   Practicum: Experiment: Definite combining proportions.†
9. Reading: Avogadro, "Essay on a Manner of Determining the Relative Masses. . . ."
   Practicum: Experiment : Weighing the molecule of a gas.‡
10. Reading: Remarks on "Molecule" and "Atom."
    Reading: Cannizzaro, Letter to Professor S. De Luca, Lectures 1–5.
    Practicum: Experiment: Carbon Dioxide from Dry Ice.
11. Reading: Cannizzaro, Lecture 6
    Practicum: Experiment: Weighing the water molecule.
12. Reading: Mendeleev, "The Periodic Law of the Chemical Elements," Introduction, Section I.
13. Reading: Mendeleev: Section II–end.
    Practicum: Experiment: Ranking elements of a particular period.
14. Reflection on Constitution of Bodies segment (and perhaps the class generally). ■

*Green Lion edition preferred. There is also a helpful note on the text at the beginning of the manual.
†The order of practica on days 7 and 8 is sometimes reversed.
‡In the current manual this experiment follows the Cannizzaro reading.

Aristotle: *On the Heavens*[1]

Book IV, Chapters 1, 3–5

§1. We have now to consider the terms 'heavy' and 'light'. We must ask what the bodies so called are, how they are constituted, and what is the reason of their possessing these powers. The consideration of these questions is a proper part of the theory of movement, since we call things heavy and light because they have the power of being moved naturally in a certain way. (The activities corresponding to these powers have not been given any name, unless it is thought that 'impetus' is such a name.) But because the inquiry into nature is concerned with movement, and these things have in themselves some spark (as it were) of movement, all inquirers avail themselves of these powers, though in all but a few cases without exact discrimination. We must then first look at whatever others have said, and formulate the questions which require settlement in the interests of this inquiry, before we go on to state our own view of the matter.

Language recognizes (*a*) an absolute, (*b*) a relative heavy and light.[2] Of two heavy things, such as wood and bronze, we say that the one is relatively light, the other relatively heavy. Our predecessors have not dealt at all with the absolute use of the terms, but only with the relative. I mean, they do not explain what the heavy is or what the light is, but only the relative heaviness and lightness of things possessing weight. This can be made clearer as follows. There are things whose constant nature it is to move away from the centre, while others move constantly towards the centre; and of these movements that which is away from the centre I call upward movement and that which is towards it I call downward movement. (The view, urged by some, that there is no up and no down in the heaven, is absurd. There can be, they say, no up and no down, since the universe is similar every way, and from any point on the earth's surface a man by advancing far enough will come to stand foot to foot with himself. But the extremity of the whole, which we call 'above', is in position above and in nature primary. And since the universe has an extremity and a centre, it must clearly have an up and down. Common usage is thus correct, though inadequate. And the reason of its inadequacy is that men think that the universe is not similar every way. They recognize only the hemisphere which is over us. But if they went on to think of the world as formed on this pattern all round, with a centre identically related to each point on the extremity, they would have to admit that the extremity was above and the centre below.) By absolutely light,

[1] Translated by J. L. Stocks, 1922. Differences from the revised version in the Oxford Complete Works are noted in the footnotes that follow. Changes in punctuation are made but go unnoted.

[2] "Things are called heavy and light both without qualification and in relation to something else."

then, we mean that which moves upward or to the extremity, and by absolutely heavy that which moves downward or to the centre. By lighter or relatively light we mean that one, of two bodies endowed with weight and equal in bulk, which is exceeded by the other in the speed of its natural downward movement.

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§3. These, then, are the views which have been advanced by others 310a 14
and the terms in which they state them. We may begin our own statement by settling a question which to some has been the main difficulty—the question why some bodies move always and naturally upward and others downward, while others again move both upward and downward. After that we will inquire into light and heavy and the explanation of the various phenomena[1] connected with them. The local movement of each body into its own place must be regarded as similar to what happens in connexion with other forms of generation and change. There are, in fact, three kinds of movement, affecting respectively the size, the form, and the place of a thing, and in each it is observable that change proceeds from a contrary to a contrary or to something intermediate: it is never the change of any chance subject in any chance direction, nor, similarly, is the relation of the mover to its object fortuitous: the thing altered is different from the thing increased, and precisely the same difference holds between that which produces alteration and that which produces increase. In the same manner it must be thought that that which produces local motion and that which is so moved are not fortuitously related. Now, that which produces upward and downward movement is that which produces weight and lightness, and that which is moved is that which is potentially heavy or light, and the movement of each body to its own place is motion towards its own form. (It is best to interpret in 310b 1
this sense the common statement of the older writers[2] that 'like moves to like'. For the words are not in every sense true to fact. If one were to remove the earth to where the moon now is, the various fragments of earth would each move not towards it but to the place in which it now is. In general, when a number of similar and undifferentiated bodies are moved with the same motion this result is necessarily produced, viz. that the place which is the natural goal of the movement of each single part is also that of the whole. But since the place of a thing is the boundary of that which contains it, and the continent of all things that move upward or downward is the extremity and the centre,[3] and this boundary comes to be, in a sense, the form of that

[1] "properties"
[2] "the old saying"
[3] "and all things that move upward or downward are contained by the extremity and the centre,"

which is contained, it is to its like that a body moves when it moves to its own place.[1] For the successive members of the scries are like one another: water, I mean, is like air and air like fire, and between intermediates the relation may be converted, though not between them and the extremes; thus air is like water, but water is like earth: for the relation of each outer body to that which is next within it is that of form to matter.) Thus to ask why fire moves upward and earth downward is the same as to ask why the healable, when moved and changed *quâ* healable, attains health and not whiteness; and similar questions might be asked concerning any other subject of alteration. Of course the subject of increase, when changed *quâ* increasable, attains not health but a superior size. The same applies in the other cases. One thing changes in quality, another in quantity: and so in place, a light thing goes upward, a heavy thing downward. The only difference is that in the last case, viz. that of the heavy and the light, the bodies are thought to have a spring[2] of change within themselves, while the subjects of healing and increase are thought to be moved purely from without. Sometimes, however, even they change of themselves, i.e. in response to a slight external movement reach health or increase, as the case may be. And since the same thing which is healable is also receptive of disease, it depends on whether it is moved *quâ* healable or *quâ* liable to disease whether the motion is towards health or towards disease. But the reason why the heavy and the light appear more than these things to contain within themselves the source[3] of their movements is that their matter is nearest to being.[4] This is indicated by the fact that locomotion belongs to bodies only when isolated from other bodies, and is generated last of the several kinds of movement; in order of being then it will be first. Now whenever air comes into being out of water, light out of heavy, it goes to the upper place. It is forthwith light: becoming is at an end, and in that place it has being. Obviously, then, it is a potentiality, which, in its passage to actuality, comes into that place and quantity and quality which belong to its actuality. And the same fact explains why what is already actually fire or earth moves, when nothing obstructs it, towards its own place. For motion is equally immediate in the case of nutriment, when nothing hinders, and in the case of the thing healed, when nothing stays the healing. But the movement is also due to the original creative force and to that which removes the hindrance or off which the moving thing rebounded, as was explained in our opening discussions, where we tried to show how none of these things moves itself.[5] The reason of the various motions of the various bodies, and

[1] "for something to move to its own place is for it to move to its like."
[2] "principle"
[3] "principle"
[4] "substance."
[5] Footnote here: 'Physics VIII 4.'

the meaning of the motion of a body to its own place, have now been explained.

§4. We have now to speak of the distinctive properties of these bodies and of the various phenomena[1] connected with them. In accordance with general conviction we may distinguish the absolutely heavy, as that which sinks to the bottom of all things, from the absolutely light, which is that which rises to the surface of all things. I use the term 'absolutely', in view of the generic character of 'light' and 'heavy', in order to confine the application to bodies which do not combine lightness and heaviness.[2] It is apparent, I mean, that fire, in whatever quantity, so long as there is no external obstacle, moves upward, and earth downward; and, if the quantity is increased, the movement is the same, though swifter. But the heaviness and lightness of bodies which combine these qualities is different from this, since while they rise to the surface of some bodies they sink to the bottom of others. Such are air and water. Neither of them is absolutely either light or heavy. Both are lighter than earth—for any portion of either rises to the surface of it—but heavier than fire, since a portion of either, whatever its quantity, sinks to the bottom of fire; compared together, however, the one has absolute weight, the other absolute lightness, since air in any quantity rises to the surface of water, while water in any quantity sinks to the bottom of air. Now other bodies are severally light and heavy, and evidently in them the attributes are due to the difference of their uncompounded parts: that is to say, according as the one or the other happens to preponderate the bodies will be heavy and light respectively. Therefore we need only speak of these parts, since they are primary and all else consequential: and in so doing we shall be following the advice which we gave to those whose attribute heaviness to the presence of plenum and lightness to that of void. It is due to the properties of the elementary bodies that a body which is regarded as light in one place is regarded as heavy in another, and vice versa. In air, for instance, a talent's weight of wood is heavier than a mina of lead, but in water the wood is the lighter. The reason is that all the elements except fire have weight and all but earth lightness. Earth, then, and bodies in which earth preponderates, must needs have weight everywhere, while water is heavy anywhere but in earth, and air is heavy when not in water or earth. In its own place each of these bodies has weight except fire, even air. Of this we have evidence in the fact that a bladder when inflated weighs more than when empty. A body, then, in which air preponderates over earth and water, may well be lighter than something in water and yet heavier than it in air, since such a body does not rise in air but rises to the surface in water.

[1] "properties"

[2] after 'absolutely': "with reference to the genus and to those bodies which do not combine lightness and heaviness."

The following account will make it plain that there is an absolutely light and an absolutely heavy body.[1] And by absolutely light I mean one which of its own nature always moves upward, by absolutely heavy one which of its own nature always moves downward, if no obstacle is in the way. There are, I say, these two kinds of body, and it is not the case, as some maintain, that all bodies have weight. Different views are in fact agreed[2] that there is a heavy body, which moves uniformly towards the centre. But there is also similarly a light body. For we see with our eyes, as we said before, that earthy things sink to the bottom of all things and move towards the centre. But the centre is a fixed point. If therefore there is some body which rises to the surface of all things—and we observe fire to move upward even in air itself, while the air remains at rest—clearly this body is moving towards the extremity. It cannot then have any weight. If it had, there would be another body in which it sank: and if that had weight, there would be yet another[3] which moved to the extremity and thus rose to the surface of all moving things. In fact, however, we have no evidence of such a body. Fire, then, has no weight. Neither has earth any lightness, since it sinks to the bottom of all things, and that which sinks moves to the centre. That there is a centre towards which the motion of heavy things, and away from which that of light things is directed, is manifest in many ways. First, because no movement can continue to infinity. For what cannot be can no more come-to-be than be, and movement is a coming to-be in one place from another. Secondly, like the upward movement of fire, the downward movement of earth and all heavy things makes equal angles on every side with the earth's surface: it must therefore be directed towards the centre. Whether it is really the centre of the earth and not rather that of the whole to which it moves, may be left to another inquiry, since these are coincident.[4] But since that which sinks to the bottom of all things moves to the centre, necessarily that which rises to the surface moves to the extremity of the region in which the movement of these bodies takes place. For the centre is opposed as contrary to the extremity, as that which sinks[5] is opposed to that which rises to the surface. This also gives a reasonable ground for the duality of heavy and light in the spatial duality centre and extremity. Now there is also the intermediate region to which each name is given in opposition to the other extreme. For that which is intermediate between the two is in a sense both extremity and centre. For this reason there is another heavy and light; namely, water and air. But in our view the continent[6]

[1] "there are absolutely light and absolutely heavy things."
[2] "Others indeed agree with us"
[3] "; and if that were so, there would be another"
[4] Footnote here: 'See above, II 14.'
[5] "always sinks"
[6] "container"

pertains to form and the contained to matter: and this distinction is present in every genus. Alike in the sphere of quality and in that of quantity there is that which corresponds rather to form and that which corresponds to matter. In the same way, among spatial distinctions, the above belongs to the determinate, the below to matter. The same holds, consequently, also of the matter itself of that which is heavy and light: as potentially possessing the one character, it is matter for the heavy, and as potentially possessing the other, for the light. It is the same matter, but its being is different, as that which is receptive of disease is the same as that which is receptive of health, though in being different from it, and therefore diseasedness is different from healthiness.

§5. A thing then which has the one kind of matter is light and always moves upward, while a thing which has the opposite matter is heavy and always moves downward. Bodies composed of kinds of matter different from these but having relatively to each other the character which these have absolutely, possess both the upward and the downward motion. Hence air and water each have both lightness and weight, and water sinks to the bottom of all things except earth, while air rises to the surface of all things except fire. But since there is one body only which rises to the surface of all things and one only which sinks to the bottom of all things, there must needs be two other bodies which sink in some bodies and rise to the surface of others. The kinds of matter, then, must be as numerous as these bodies, i.e. four, but though they are four there must be a common matter of all—particularly if they pass into one another—which in each is in being different. There is no reason why there should not be one or more intermediates between the contraries, as in the case of colour; for 'intermediate' and 'mean' are capable of more than one application.

Now in its own place every body endowed with both weight and lightness has weight—whereas earth has weight everywhere—but they only have lightness among bodies to whose surface they rise. Hence when a support is withdrawn such a body moves downward until it reaches the body next below it, air to the place of water and water to that of earth. But if the fire above air is removed, it will not move upward to the place of fire, except by constraint; and in that way water also may be drawn up, when the upward movement of air which has had a common surface with it is swift enough to overpower the downward impulse of the water. Nor does water move upward to the place of air, except in the manner just described. Earth is not so affected at all, because a common surface is not possible to it. Hence water is drawn up into the vessel to which fire is applied, but not earth. As earth fails to move upward, so fire fails to move downward when air is withdrawn from beneath it: for fire has no weight even in its own place, as earth has no lightness. The other two move downward when the body beneath is withdrawn because, while the absolutely heavy is that which sinks to the bottom of all things, the relatively heavy sinks to its own place or to the surface of the body in which it rises, since it is similar in matter to it.

It is plain that one must suppose as many distinct species of matter as there are bodies. For if, *first*,[1] there is a single matter of all things, as, for instance, the void or the plenum or extension or the triangles, either all things will move upward or all things will move downward, and the second motion will be abolished. And so, either there will be no absolutely light body, if superiority of weight is due to superior size or number of the constituent bodies or to the fullness of the body (but the contrary is a matter of observation, and it has been shown that the downward and upward movements are equally constant and universal); or, if the matter in question is the void or something similar, which moves uniformly upward, there will be nothing to move uniformly downward. Further, it will follow that the intermediate bodies move downward in some cases quicker than earth: for air in sufficiently large quantity will contain a larger number of triangles or solids or particles. It is, however, manifest that no portion of air whatever moves downward. And the same reasoning applies to lightness, if that is supposed to depend on superiority of quantity of matter. But if, *secondly*,[2] the kinds of matter are two, it will be difficult to make the intermediate bodies behave as air and water behave. Suppose, for example, that the two asserted are void and plenum. Fire, then, as moving upward, will be void, earth, as moving downward, plenum; and in air, it will be said, fire preponderates, in water, earth. There will then be a quantity of water containing more fire than a little air, and a large amount of air will contain more earth than a little water; consequently we shall have to say that air in a certain quantity moves downward more quickly than a little water. But such a thing has never been observed anywhere. Necessarily, then, as fire goes up because it has something, e.g. void, which other things do not have, and earth goes downward because it has plenum, so air goes to its own place above water because it has something else, and water goes downward because of some special kind of body. But if the two bodies are one matter, or two matters both present in each, there will be a certain quantity of each at which water will excel a little air in the upward movement and air excel water in the downward movement, as we have already often said.

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[1] '*first*' deleted
[2] '*secondly*' deleted

Bacteria as Multicellular Organisms

They differentiate into various cell types and form highly regular colonies that appear to be guided by sophisticated temporal and spatial control systems

by James A. Shapiro

Without bacteria, life on earth could not exist in its present form. Bacteria are key players in many geochemical processes, including the fundamental nitrogen, carbon and sulfur cycles, which are critical to the circulation of life's basic elements. If these processes were to grind to a halt, the planet's soils, waters and atmosphere would become inhospitable for life. Yet in spite of such global importance, the notion has persisted that bacteria are simple unicellular microbes.

That view is now being challenged. Investigators are finding that in many ways an individual bacterium is more analogous to a component cell of a multicellular organism than it is to a free-living, autonomous organism. Bacteria form complex communities, hunt prey in groups and secrete chemical trails for the directed movement of thousands of individuals.

Already at the beginning of this century investigators had evidence that bacteria live communally in the soil. Martinus Beijerinck of the Netherlands discovered that *Rhizobium* bacteria infect the roots of leguminous plants, where they form organized multicellular structures that function as factories for nitrogen production. At about the same time Sergei Winogradsky, working in Paris, elucidated the role bacteria play as decomposers of cellulose in the global carbon cycle. Winogradsky was also one of the first microbiologists to observe bacteria directly in the soil, where he found that few exist as isolated cells; most live in groups adhered to soil particles. Similar group behavior was well known in the laboratory, where bacteria formed distinctive colonies on petri dishes or adhered as organized populations to the walls of culture flasks.

In spite of these early observations, the image of bacteria as unicellular organisms has persisted over the years. In large part this can be attributed to medical bacteriology. Disease-causing organisms are commonly identified by isolating a single cell of the suspected pathogen, growing a culture from that cell and showing that the resulting pure culture gives rise to the disease in question. The possibility that infections of the human body involve multicellular aggregations of bacteria is normally not even considered.

Indeed, many existing theories of bacterial growth, physiology and genetics are formulated exclusively in terms of the isolated bacterium. From an epistemological standpoint this emphasis on the single cell is curious. In practice most research is carried out on cell populations. An enzyme measurement, for example, may be based on an extract from 100 million cells, but conclusions based on the results are often made under the assumption that every bacterium in a population is more or less the same. Such a premise may simplify the interpretation of experimental results, but it is a simplification that is likely to prove invalid in many cases. How exceptional—or how common—are multicellular features in bacteria? In investigating this question I have concluded that most—perhaps virtually all—bacteria lead multicellular lives.

Examples of multicellularity among the bacteria abound; indeed, some of the complex biochemical processes performed by bacteria could not be carried out as effectively without organized groups. Photosynthesis is a process that illustrates this point in several ways. Photosynthetic bacteria, like green plants, rely on solar energy to convert carbon dioxide into organic chemicals. One group of photosynthetic bacteria, known as the cyanobacteria, often grow as connected chains of cells or as intertwined mats; they contain a form of chlorophyll and in many ways resemble multicellular algae. For many years, in fact, the cyanobacteria were thought to be members of the plant kingdom. The multicellular organization aids in light harvesting but yields other benefits too.

Anabaena, an inhabitant of freshwater ponds, is one of the best-known of the photosynthetic bacteria. *Anabaena* is capable of both photosynthesis and nitrogen fixation. These two biochemical processes are incompatible within a single cell because oxygen, produced during photosynthesis, inactivates the nitrogenase required for nitrogen fixation. When nitrogen compounds are abundant, *Anabaena* is strictly photosynthetic and its cells are all alike. When nitrogen levels are low, however, specialized cells called heterocysts are produced. The heterocysts lack chlorophyll but synthesize nitrogenase, an enzyme with which they are able to convert nitrogen gas into a usable form.

James W. Golden and Robert Hasel-

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korn of the University of Chicago have shown that differentiation in *Anabaena* involves a form of controlled genetic engineering. In the course of heterocyst differentiation a specific DNA rearrangement occurs that results in the creation of a complete coding sequence for one of the subunits of nitrogenase. Such a rearrangement occurs only in cells that are differentiating to form heterocysts. Comparable DNA rearrangements are involved in the formation of specialized immune-system cells in vertebrates.

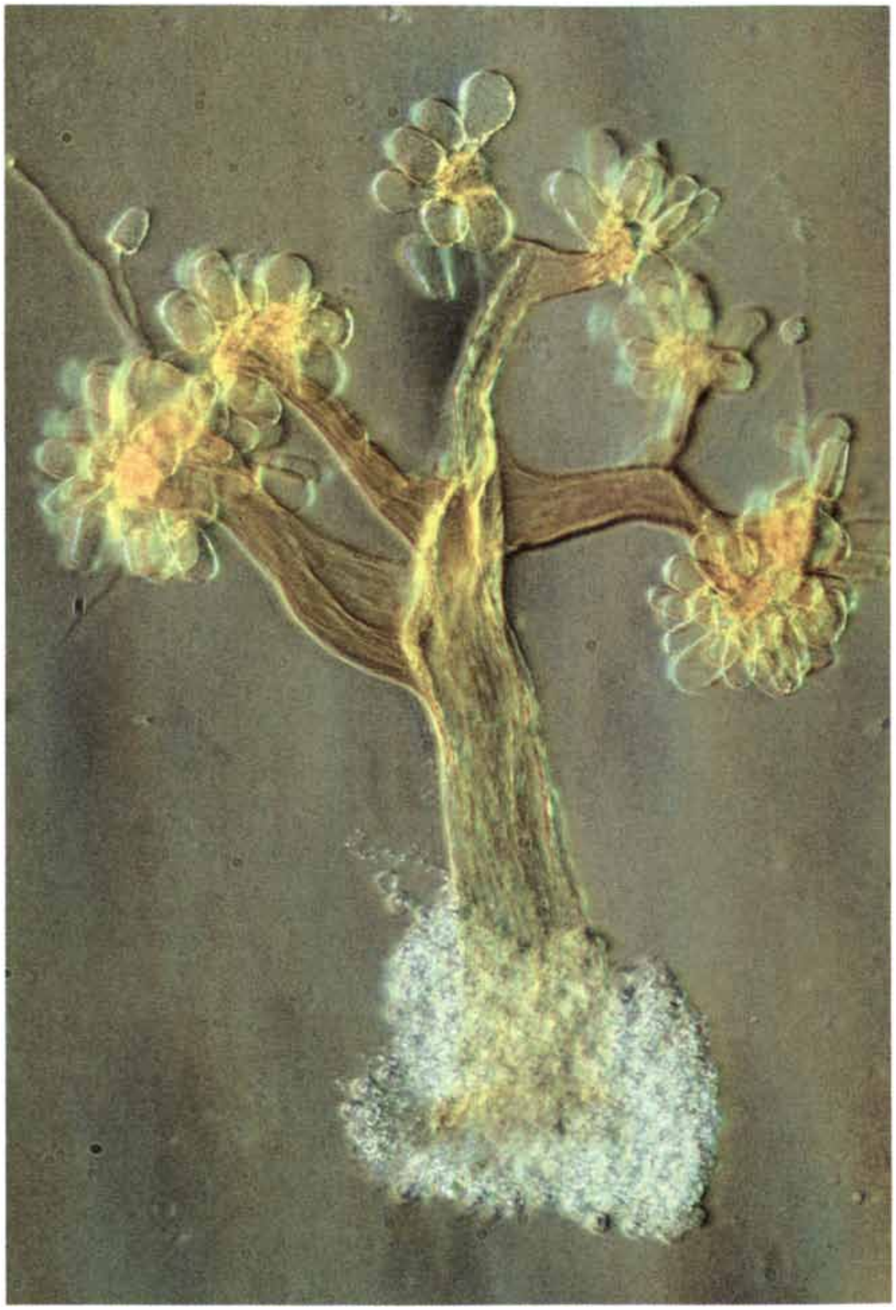
In addition there are submicroscopic channels within each *Anabaena* filament that connect the two kinds of cells. The transport of cellular products (fixed nitrogen to the photosynthetic cells and photosynthetic products to the heterocysts) takes place by way of these channels. In overall character, then, it can be said that *Anabaena* functions more like a multicellular organism than a unicellular one: it relies on division of labor among its cells to carry out specialized and incompatible chemical processes.

More spectacular examples of multicellular behavior can be found among the Myxobacteria, the most morphologically complex of all bacteria. Their elaborate fruiting bodies rival those of fungi and slime molds and have long been an object of scientific curiosity. Myxobacteria are social creatures par excellence and their intriguing, almost psychedelic patterns of aggregation and movement have been recorded in a fascinating series of time-lapse motion pictures produced by Hans Reichenbach of the Society for Biotechnological Research in Braunschweig and his collaborators at the Institute for Scientific Film (I.W.F.) in Göttingen.

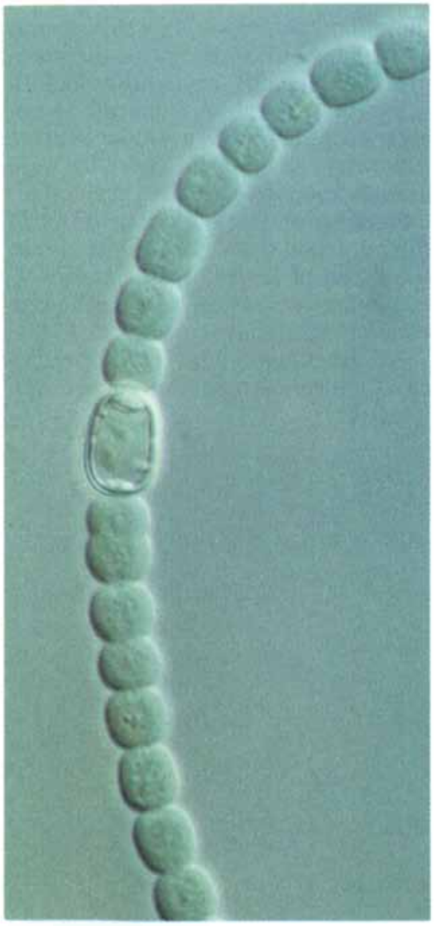
Unlike many bacteria, which periodically enter a dormant stage as individual spores, many Myxobacteria never exist as single cells. Instead they enter dormancy in the form of a multicellular cyst that eventually germinates and spawns a ready-made population of thousands of individuals. Each cyst founds a new population; as the bacteria become more numerous and dense, a number of sophisticated events specific to multicellularity take place. Trails of extracellular slime are secreted and serve as highways for the directed movement of thousands of cells, rhythmic waves pulse through the entire population, streams of bacteria move to and from the center and edges of a spreading colony, and bacteria aggregate at specific places within the colony to construct cysts or, in some species, to form elaborate fruiting bodies. Movement is highly coordinated: when the population migrates over agar, it displaces itself as an intact unit. When an individual cell moves a few microns beyond the edge, it quickly pops back into place as though drawn by an elastic thread.

Even those species of Myxobacteria that do enter dormancy as single-cell spores are social throughout much of their life cycle. When two cells of *Myxococcus virescens* meet, for example, they go through a characteristic ritual: they align themselves side by side and either move off in the same direction or rub alongside each other before separating. Daughter cells can be observed taking part in a similar routine following cell division. These bacteria literally keep in touch with each other!

Predator-prey relationships exist in the microbial world just as they do in the world of larger organisms. Several predatory species of Myxobacteria feed by secreting enzymes that dissolve the outer cell layer of other microorganisms; when the cells burst,



MULTICELLULAR FRUITING BODY of *Chondromyces crocatus,* a species in the group Myxobacteria, is magnified 268 diameters. The structure consists of a central stalk that branches to form specialized clusters of single-cell spores. When the clusters burst, the spores disperse to form new colonies. The micrograph was made by Hans Reichenbach of the Society for Biotechnological Research in Braunschweig.



ANABAENA, a photosynthetic cyanobacterium, forms filaments of cells in freshwater ponds. Most of the cells are photosynthetic, but when nitrogen levels are low, heterocysts develop. The heterocysts, which are capable of nitrogen fixation but not photosynthesis, are larger than the photosynthetic cells and have special storage granules for nitrogen-rich compounds. The Nomarski micrograph was made by the author; the cells are enlarged 1,625 diameters.

the myxobacteria absorb their contents. One species, *Myxococcus xanthus,* has evolved a specialized method of prey capture in response to its aquatic environment. In water it cannot release its digestive enzymes because they would immediately be diluted, as would the prey's nutrients. Jeffrey C. Burnham and his colleagues at the Medical College of Ohio have shown that instead *M. xanthus* constructs spherical colonies containing millions of bacteria. The colonies surround suitable prey organisms, trapping them in pockets on the surface of the sphere, where both the digestive enzymes and the prey contents can be effectively corralled.

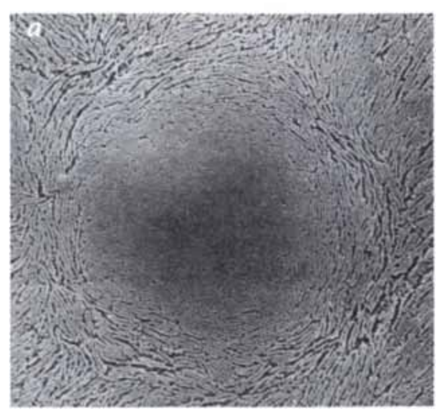
Over the past decade A. Dale Kaiser of the Stanford University Medical School and his colleagues have studied the genetic basis of communication and movement in *M. xanthus.* By searching for mutants that have lost the ability to spread or to form fruiting bodies, they have identified specific regions of the organism's DNA that control for aggregation, motility and differentiation. They found that motility in *M. xanthus* is under the control of two different systems. The *A* (for adventurous) system enables individual cells to move across the substrate; the *S* (for social) system controls the movement of groups of cells. If either system is defective, the cells are still able to spread, but they do so abnormally. If both systems are defective, the cells cannot spread at all. The two systems are surprisingly complex and a great deal of specific genetic information is required for each to be operative. A mutation affecting any one of 23 different genetic loci will eliminate the *A* motility system; at least 10 different loci control the *S* system.

Kaiser and his colleagues have also begun to unravel some of the ways *M. xanthus* cells communicate with one another. They accomplished this by combining different mutant cells that were defective for the same trait but in which the defect resulted from mutations at different loci. They found that when two motility-defective mutants are combined in the same petri dish, they regain motility as long as both mutants stay together. Similarly, if two sporulation-defective mutants are mixed in culture, they will form normal fruiting bodies and sporulate. In some instances such mixed-cell complementation is now known to be mediated by the production of extracellular substances; in other cases it may result either from direct cell-to-cell contact or from the physical presence of two complementary cell types.

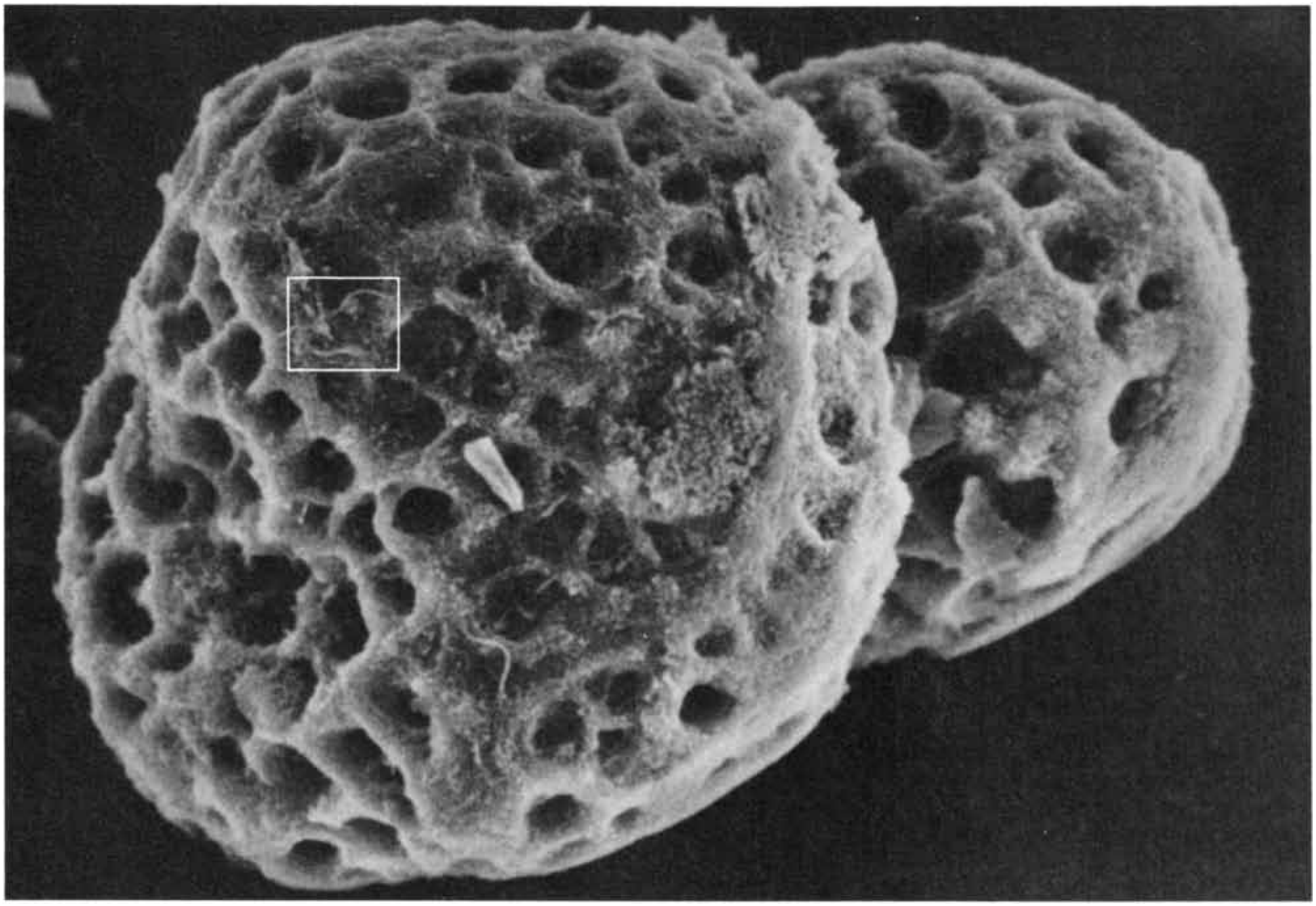
My own studies of multicellular behavior in bacteria began, as is often the case, as the result of a chance observation. A little over five years ago I was experimenting with a genetic-engineering tool, designed by Malcolm J. Casdaban of the University of Chicago and his students, in order to study enzyme expression in *Pseudomonas.* The technique enabled me to join the genes for certain *Pseudomonas putida* enzymes with the DNA sequence from *Escherichia coli* that encodes the enzyme beta-galactosidase. The advantage of beta-galactosidase as a genetic-engineering tool is that it causes certain chemicals to turn color when they are exposed to it. If the beta-galactosidase sequence is linked to the gene for the enzyme under study and the recombinant DNA is inserted into *Pseudomonas,* then when the bacteria are grown on agar containing those chemicals, the amount and distribution of color is a direct measure of the gene's expression.

When I plated my recombinant strains of *P. putida* on such indicator agar, I was astonished to find that every colony exhibited a characteristic flowerlike pattern of staining. I repeated the experiment with engineered *E. coli* and with strains of naturally pigmented bacteria, such as *Pseudomonas cepacia, Serratia marcescens* and *Chromobacterium violaceum.* Each produced its own unique flowerlike pattern. The fact that different strains and species produced distinctive colonies (including species that were naturally colored and not subjected to genetic manipulation) gave me reason to believe colony growth in bacteria is a highly regulated process and is under some form of temporal control. Subsequent studies confirmed that hypothesis. It is now clear to me that colony organization follows certain general rules, which help to explain the existence of general patterns.

The colonies tend to assume a circular configuration, growing outward by adding cells to the perimeter. As a colony spreads across the agar, it is apparent that the pattern of growth consists of both concentric and radial elements. The concentric elements are rings that encircle the colony; the radial elements, or sectors, look like slices of pie. Each sector consists of outwardly growing progeny descended from a common ancestor. Some grow better than others and expand, whereas other sectors merely hold their own or even disappear as the colony gets bigger.



FORMATION OF FRUITING BODY in the Myxobacteria follows a characteristic sequence of steps, as is shown from the far left in these scanning electron micro-

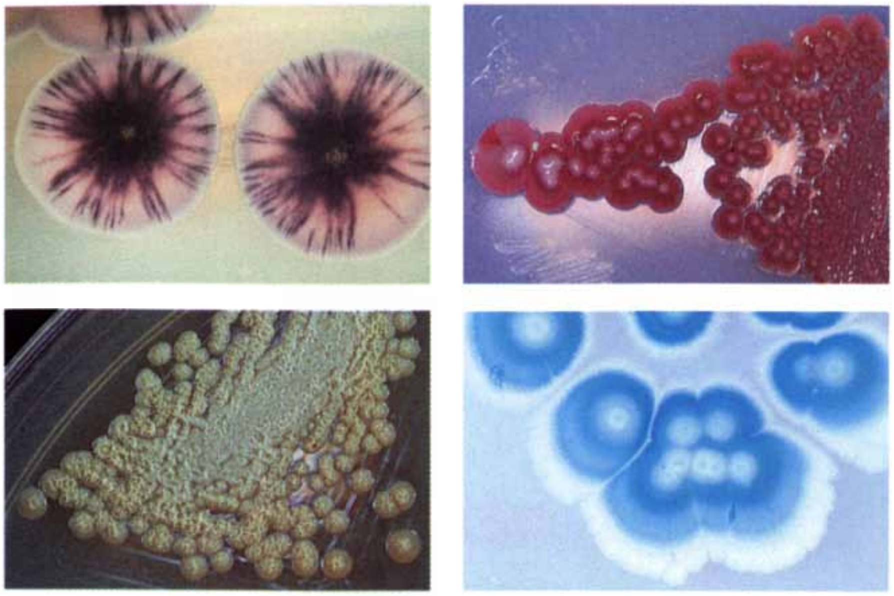


PREDATORY SPHERES are formed by millions of individual cells of *Myxococcus xanthus* as a means of capturing prey in an aquatic environment. Microscopic prey, such as the cyanobacterium *Phormidium luridum* (*inset*), stick to the colony and are eventually digested within pockets on the sphere's surface. The spheres are enlarged 440 diameters in this scanning electron micrograph made by Jeffrey C. Burnham, Susan A. Collart and Barbara W. Highison of the Medical College of Ohio.

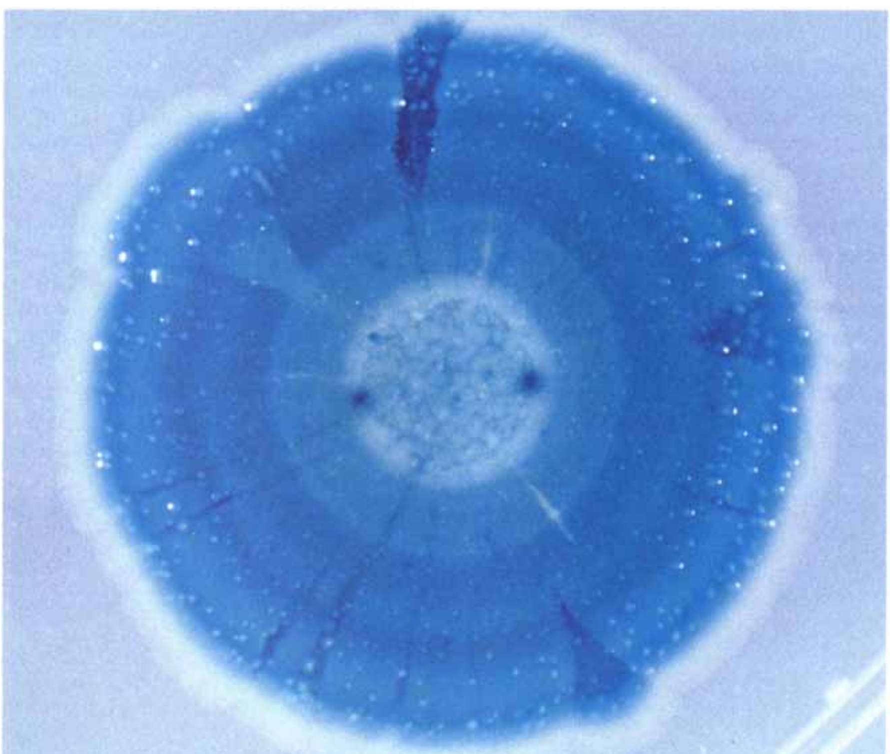
In many cases it is possible to select individual cells from different sectors, grow them in culture and show that the cells in one sectorial culture have heritable properties differing from those of the cells in another sectorial culture; often cells from different sectors can be distinguished on the basis of differences in their DNA. Recently N. Patrick Higgins of the University of Alabama Medical School and I found that differences in DNA between distinct sectors and concentric zones can sometimes be visualized directly by picking colonies up on filter paper, extracting their DNA in situ and then applying radioactive probes to detect specific sequences.

The concentric elements in a colony are less familiar than the sectors and hence more puzzling. The cells in a concentric zone or ring share a common property (such as the level of expression of beta-galactosidase activity) but are not related by common ancestry; they are directly related to bacteria in the preceding and succeed-

graphs tracing the morphogenesis of *Stigmatella aurantiaca.* At first cells form aggregation centers. As the centers accumulate bacteria they bubble upward until the vertical stalk is complete. In some species, such as this unidentified one from the Indiana University campus, the stalk is elaborately branched (*far right*). The *S. aurantiaca* fruiting body is enlarged 450 diameters. Micrographs were made by Gabriela M. Vasquez, Frank Qualls and David White of Indiana University.



FLOWERLIKE COLONIES can be produced by streaking bacterial cultures over an agar plate. Each colony (when it is not crowded) assumes a pattern characteristic of its strain. *Chromobacterium violaceum* (*top left*) naturally produces the pigment violacein and forms purple colonies. *Serratia marcescens* (*top right*) synthesizes prodigiosin; it forms bright red colonies once thought to be drops of blood. *Pseudomonas cepacia* (*bottom left*) is yellow and has a unique surface texture, the result of cell aggregation at the surface. An *Escherichia coli* colony (*bottom right*) carries genetically engineered DNA sequences encoding the enzyme beta-galactosidase; where the enzyme is expressed the colony turns blue. The colonies are at various magnifications.



***E. COLI* colony was grown from a single drop of culture that contained thousands of cells. The highly regular, intricate pattern of pigmented rings is characteristic of certain genetically engineered *E. coli* colonies stained for beta-galactosidase activity. Pie-shaped sectors, within which the control of enzyme synthesis has changed, are also apparent. The sectors at five o'clock and ten o'clock have curved edges, indicating that the bacteria within these regions spread faster than the rest of the colony. The concentric rings that run through the ten o'clock sector are displaced outward, suggesting that changes in enzyme activity occurred at similar times both inside and outside the sector. This colony was approximately a centimeter in diameter.**

ing zones, not to one another. If the organization of the colony into distinct concentric zones cannot be explained by heredity, how might it be explained? Some system must exist that bestows common properties on bacteria within a ring and distinguishes them from bacteria in other rings.

One set of clues to the origins of concentric patterns lies in the different ways the sectorial and concentric elements interact with one another. Photographs of colonies often show that concentric rings persist through sectors that grow faster than the rest of the colony. The resulting pattern contains rings that are stretched outward. The stretching shows that the rings are formed not at specific positions on the agar (that is, at particular distances from the center) but at a specific time in the course of colony development. This suggests bacteria have biological clocks that enable them in some way to program cellular differentiation at specific times during development. The rhythmic pulsations of spreading myxobacterial colonies also reflect the operation of a clocklike mechanism. Both biological clocks and the temporal control of development, previously unknown in bacteria, are important features of higher organisms.

Examination of the surface textures of a colony indicates that cellular differentiation also takes place at the level of cellular aggregation. When light is reflected from a colony, various surface textures that are as organized as the pigmentation patterns and also show radial and concentric elements become visible. In many cases the two patterns coincide: a sector defined by color may also display a novel surface structure, and a ring may stand out on the basis of both its distinctive color and its topography.

Clearly colony organization involves more than the distribution of cells with simple biochemical differences. In order to study structural patterns more precisely, I turned to the scanning electron microscope, which visualizes surfaces at high magnification with great depth of field. The scanning electron micrographs revealed that colonies of *P. putida* and *E. coli* are made up of highly differentiated cells that often form distinctive multicellular arrays coincident with the macroscopic organization of the colony. They also revealed that each colony secretes extracellular materials, some of which form a skin or framework over its surface.

It was clear from these studies that

biochemical activity within a bacterial colony is highly organized and spatially restricted: cells in different regions of the colony have different shapes and biochemical properties. In order to identify the unknown factors that control multicellular growth in bacteria, I began to study swarm colonies. As the name implies, these are colonies that grow quickly and cover a large surface area, two characteristics that make them ideal for laboratory experimentation.

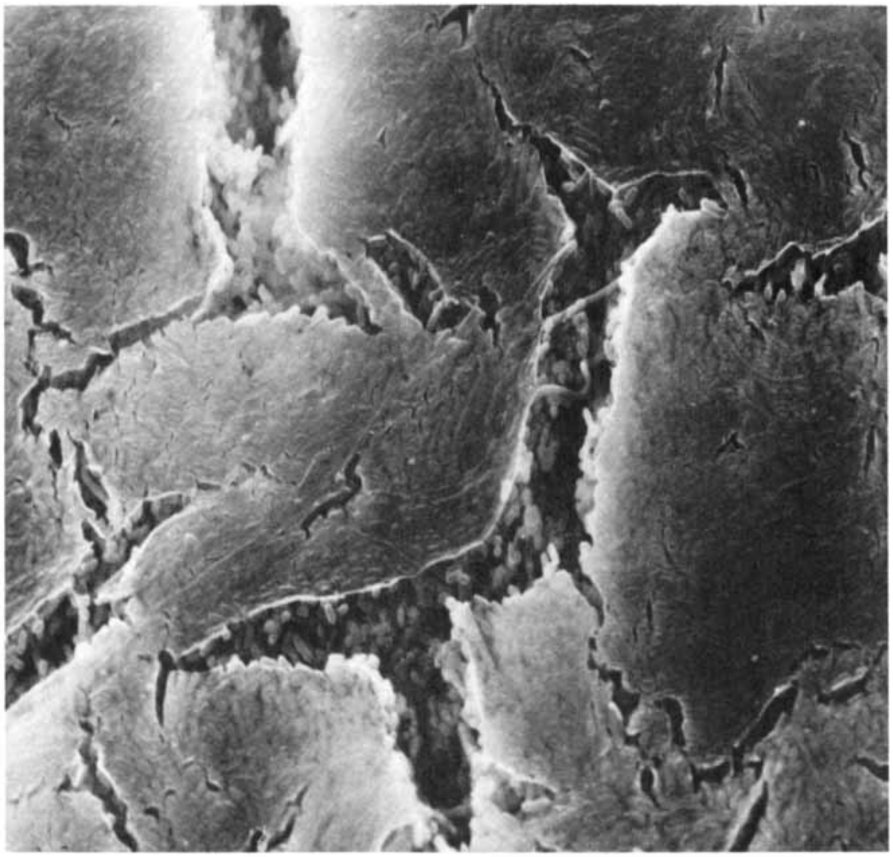
Swarm behavior can be observed in many taxonomically distant species of bacteria. I have focused on one species: *Proteus mirabilis*. Like the Greek god Proteus, this bacterium assumes different forms, producing striking configurations in a petri dish. Over the years two key features of *Proteus* colonies have been noted. One is that there are at least two very different types of cells in a colony: long swarmer cells covered with hundreds of flagellae and short nonswarmer cells with few flagellae. The second feature is that colony development occurs as a tightly programmed rhythmic process.

Swarm colonies develop from an initial population of short nonswarmer cells. As the short cells divide, long swarmer cells begin to appear. They migrate to the periphery of the colony, where they assemble in groups and then pioneer the expansion of the colony by moving out in a series of swirls. The flagellae that cover the surface of swarmer cells rotate and in so doing somehow propel the cells. (It is easy to understand how the spinning flagellae propel a cell through liquid; how such delicate structures are able to propel bacteria over the highly viscous agar surface, however, remains a total mystery.) Observing swarm colonies under a microscope, one sees thousands of flagellae on dozens of swarmer cells moving in synchrony, creating oscillating waves as the cells spread outward from the periphery. Such exquisite coordination prompted Alexander Fleming, the discoverer of penicillin, to wonder in print if *Proteus* could possibly have a nervous system!

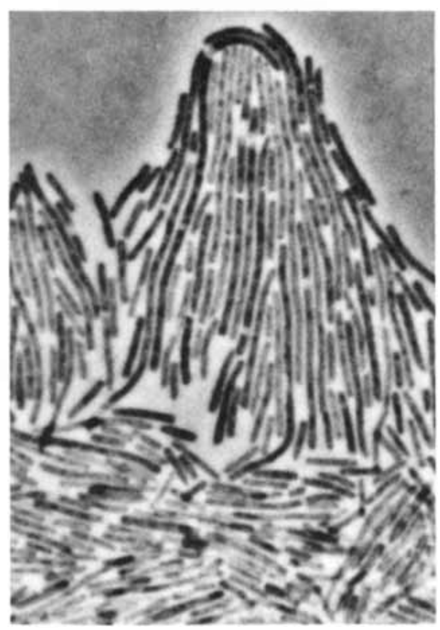
By recording *Proteus* morphogenesis with a time-lapse video camera I have been able to identify distinct periodicities in colony growth, confirming the findings of earlier workers. I discovered that intense activity within a swarm colony can be seen both at the advancing edge, where swarmer cells are rapidly moving outward, and inside the edge, where cell division and streaming activities continue—even when the swarmer cells have stopped advancing. Swarmer cells do not spread indefinitely; they stop after moving a set distance and start spreading again only after a delay, which may be as long as a few hours, depending on conditions such as temperature and the composition of the agar. Swarming is strictly a multicellular activity; an individual cell that gets separated from the rest is unable to advance over the agar unless it is engulfed by another swarmer group, at which time it starts to move again.

Activity inside the edge has its own periodicities and rhythms but is connected to the expansion of the colony as a whole. When the swarmer cells finish one phase of spreading, for example, a series of visible waves composed of more densely aggregated cells moves from inside the swarm zone toward the perimeter. Then there is a thickening of the cell mass in the recently colonized zone and a bubbling of the surface inside the perimeter. These and other exquisitely choreographed postmigration processes produce elaborate textures in the form of terraces on the surface of a fully developed swarm colony.

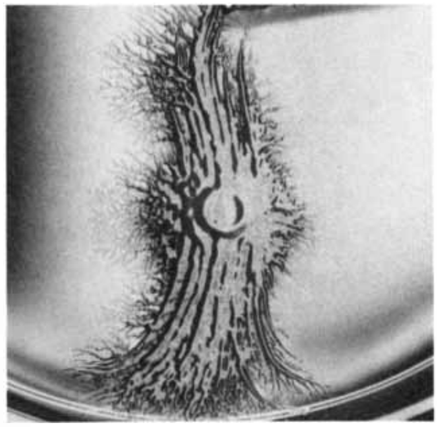
Watching the swarming process, I



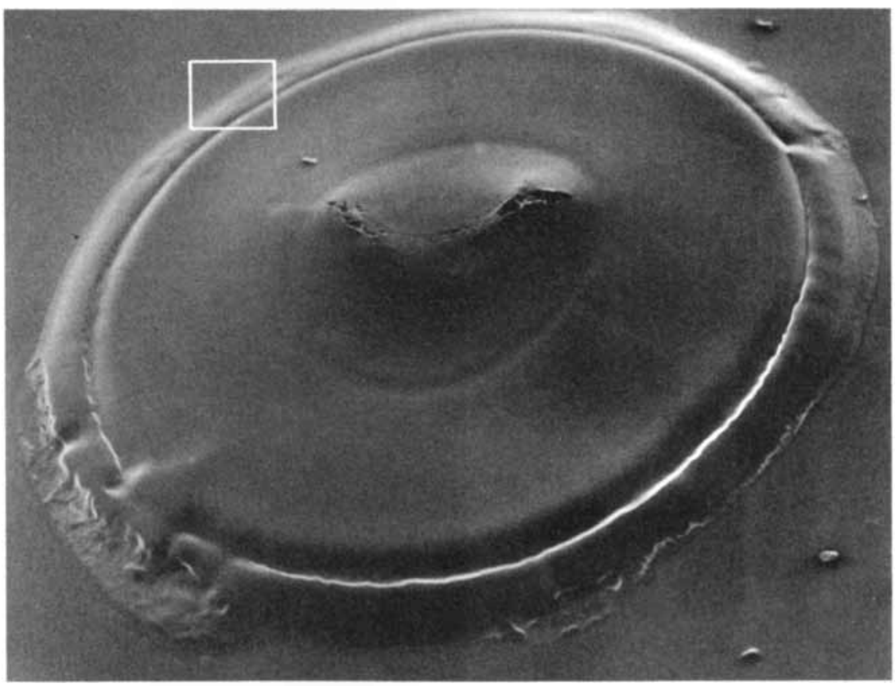
SCANNING ELECTRON MICROGRAPH of a *Pseudomonas putida* colony reveals that extracellular material covers its surface like a skin. This superstructure may in some way facilitate communication among cells of the colony. One long, curved cell can be seen bridging a crack in the skin; such cells may also be involved in intercellular communication within the colony. The colony is enlarged 2,300 diameters.

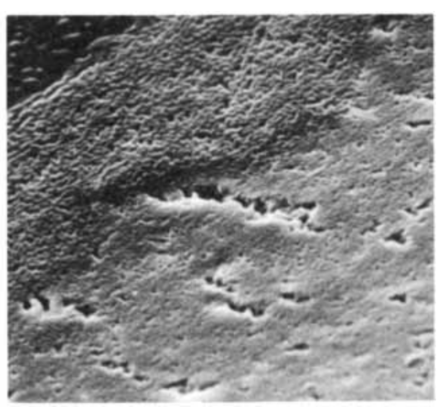


LONG SWARMER CELLS can be seen at the edge of a *Proteus mirabilis* colony. The cells are preparing to move across the agar as a group; they do so by rotating their flagellae in synchrony. The cells are enlarged 600 diameters in this micrograph made by S. A. Sturdza of the Cantacuzino Institute in Bucharest.



PROTEUS MIRABILIS **mutants show geometries that provide clues to the way colony spreading is controlled. The mutant (*left*) forms regular repeating terraces in a nine-centimeter petri dish. If a trench is cut in the agar, however, spreading stops after a few cycles. The fact that swarming is blocked in the shadowed zone indicates that a chemical signal must emanate from the center. Morphogenesis appears to be under whole-colony control; it is not regulated solely by the migrating edge. The mutant (*right*) has lost its circular symmetry and has a markedly different pattern. The bacteria began by forming thick columns along stress lines in the agar; after these columns grew to a certain size they ramified into smaller perpendicular processes that in turn formed smaller branches. This pattern suggests that although the mutant lacked the ability to produce circular colonies, it retained some kind of directional control. The length of this colony was about four centimeters.**



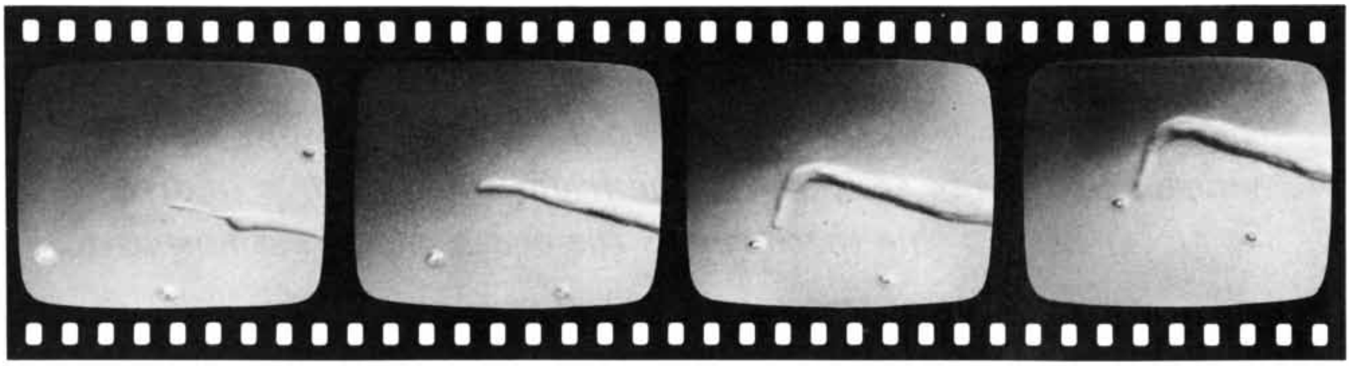


DISTINCTIVE MORPHOLOGY of cells in different zones is demonstrated in a series of scanning electron micrographs of an *E. coli* colony. The 68-hour colony (*top*), formed from an initial population of 100,000 cells, was five millimeters in diameter. When the leading edge is enlarged 100 diameters (*bottom left*), a distinct boundary is visible between two groups of differentiated cells. At greater magnification (750 diameters) the outermost zone (*bottom right*) is seen to be made up of large cells arranged irregularly, whereas the inner zone has smaller cells grouped in roughly parallel arrays.

wondered whether it would be possible to learn about the systems that control this intricate and regular behavior. In biological research important clues can come from looking at the response of organisms to unusual circumstances. If conditions in the petri dish changed, would a swarm colony alter its behavior?

Two kinds of evidence suggest that swarming behavior is indeed regulated. One is that when swarming is interrupted by chemical or physical obstacles, or by interference with the growing cell mass, specific morphological responses take place. Observation of the geometries of the swarm colonies after they have been artificially manipulated (or following spontaneous accidents that deform the regular outlines of the colonies) makes it clear that both temporal and directional controls influence colony growth. In particular, chemicals diffusing through the agar appear to play important roles in guiding colony spread.

The second line of evidence is that morphogenesis is under hereditary control. For one thing, each naturally isolated strain of *P. mirabilis* has its own characteristic mode of swarm-colony development. For another, one can obtain from these natural isolates various mutants that can still spread but that have geometries markedly different from those of their progenitors. Some mutants form periodic swarm terraces that are more closely spaced than those of their parents, whereas others have no terraces at all. One particularly striking mutant has lost its circular symmetry altogether and grows in a branching pattern influenced by stress lines in the agar. Clearly the genes that regulate morphogenesis have been altered in these mutants, whereas the ability to swarm has not been eliminated. A detailed biochemical explanation for how morphogenetic control systems might operate in *Proteus* (or in *Myxococcus* or *E. coli,* for that matter) has not yet



PURPOSEFUL MOVEMENT of *M. xanthus* cells is shown in a series of frames on a video monitor. At the bottom of the screen is a latex bead, five micrometers in diameter, toward which the cells, collectively called a flare, will orient. The tip of the flare turns toward the bead at 18 minutes (*second frame*); at 33 minutes (*fourth frame*) the flare reaches it. After sensing that the bead is inedible the flare will move on. These images were made by Martin Dworkin of the University of Minnesota.

been found. Nevertheless, the hereditary specificity of the developmental phenomena suggest that studying these systems will yield important lessons about coordinating the behaviors of large numbers of bacteria in a spatially and temporally defined way.

The view that bacteria are sentient creatures, able to receive, process and respond meaningfully to external signals, has been gaining ground over the past two decades as investigators spend more time exploring the mysteries of bacterial behavior.

Martin Dworkin of the University of Minnesota has recently provided a graphic demonstration of multicellular responsiveness in the microbial predator *Myxococcus xanthus.* He found that roaming flares, or groups, of *M. xanthus* cells perceive clumps of prey bacteria (or even glass or plastic beads) on an agar surface, make sharp turns toward the objects and then move directly to them. Once there, the *Myxococcus* flares are able to tell whether the objects are edible or not. If the objects are edible, the flares stay to feed; if they are not, the flares turn away and continue their searching behavior. Such purposeful behavior has traditionally been thought to operate only in larger organisms.

What practical value, if any, do these findings have? The biotechnology industry, eager to turn to genetically engineered bacteria as factories for the production of complex biochemicals, will undoubtedly benefit from the knowledge that bacterial cells specialize and control protein synthesis with the aid of intercellular communication signals. In the field of biodegradation the application of bacteria to remove toxic chemicals from polluted soils and water sources may be enhanced by greater understanding of multicellular processes. It may even be possible to introduce multicellularity characteristics that optimize productivity or improve the capacity of specific strains to degrade synthetic compounds. Understanding the behavior of bacteria may also make it easier to monitor the release of genetically engineered organisms.

In medicine greater understanding of bacterial behavior may lead to increased efficacy of drug treatments. J. William F. Costerton and his colleagues at the University of Calgary in Alberta recently described a patient who suffered from recurrent bloodstream infections because a colony of *Staphylococcus aureus* had formed on the lead of his cardiac pacemaker. Individual cells would break away from the parent colony periodically and infect his bloodstream. Although the individual cells were sensitive to penicillin, the colony itself was drug-resistant: like many bacterial colonies, it was protected by a coating of extracellular slime. In order to end the chronic infection the only solution was to remove the pacemaker (and its colony).

In other cases of bacterial pathogenesis there is a clear correlation between the tendency of cells to aggregate and their ability to establish an infection. It has been known for 25 years that the organism that causes gonorrhea, *Neisseria gonorrhoeae,* forms several types of colonies on laboratory media. Cells from one type are virulent, whereas those from another are not. Since a successful infection requires that the disease organism colonize its host, I suspect pathogenesis is directly related to this organism's ability to form multicellular organizations (as reflected in the kinds of colonies it builds).

Bacteriology's early pioneers, such as Louis Pasteur, recognized that there are many lessons to be learned from these smallest of living cells. Today much more is known about the intricacy and complexity of this group of organisms. If, as I have proposed here, bacteria possess elaborate developmental and behavioral capabilities typical of higher organisms, then it is likely that detailed explanations of how these small cells communicate will influence views of information processing in all organisms.

Although bacteria are tiny, they display biochemical, structural and behavioral complexities that outstrip scientific description. In keeping with the current microelectronics revolution, it may make more sense to equate their small size with sophistication rather than with simplicity. There is little reason to doubt that insights gained from studying the interactions of billions of bacteria, living together in a volume of less than a few cubic millimeters, will enhance understanding of all forms of life.

FURTHER READING

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ORGANIZATION OF DEVELOPING *ESCHERICHIA COLI* COLONIES VIEWED BY SCANNING ELECTRON MICROSCOPY. James A. Shapiro in *Journal of Bacteriology,* Vol. 169, No. 1, pages 142–156; January, 1987.

The following films are available in the U.S. from Audio-Visual Services, Pennsylvania State University:

BACILLUS CIRCULANS—AUFBAU UND VERHALTEN (*B. CIRCULANS*—GROWTH AND BEHAVIOR). Silent film, E183. Institut für den Wissenschaftlichen Film.

PROTEUS—BEWEGUNGSVERHALTEN (*PROTEUS* SWARMING BEHAVIOR). Silent film, E271. Institut für den Wissenschaftlichen Film.

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Regeneration occurs in varying degrees throughout the animal kingdom and ranges from nearly total regeneration in some forms to the limitation of wound healing in other forms such as mammals. Planaria (flatworms) have the remarkable capacity to regenerate parts of their bodies which have been removed or drastically severed.

PROCEDURES

1. Find out which group you are in and familiarize yourself with the surgery type assigned to your group (group 1 performs surgery type 1 (Fig. 1); group 2, surgery type 2 (Fig. 2); etc.). All cuts are diagrammed (Figs. 1 to 9) on the Student Surgery Sheet (over).

2. Label petri dishes as to the portion of the cut each will contain. Also place your ~~name,~~ group number, and the date on your dish(es). Fill each with the holding solution.

3. Remove an ice container from the freezer and snap it shut. Set it face up on the stage of a dissecting microscope.

4. With a camel's-hair brush carefully place one planarian in the center of the ice container surface.

5. Focus on the animal and carefully note its position and how it slows down on the cold surface. Wait until the animal has flattened out before proceeding.

6. To cut, use the gits knife to make a quick slash. Any cuts which are intended to separate two or more portions without detaching them completely from the rest of the worm (Figs. 6 to 9) will have to be periodically renewed during the first 2 days because of the tendency of the parts to fuse back together.

7. After each operation carefully transfer, with the camel's-hair brush, the planarian or its parts to the appropriately labeled petri dish.

8. Place the petri dish in a cool, dark container for the duration of the exercise.

9. The holding solution must be replaced two or three times per week. Pour old holding solution from the petri dishes and discard dead animals. Pour in fresh holding solution.

10. About one month is required to complete regeneration and during this time the planaria *should not* be fed. Development of pigments in the newly regenerated portions may take slightly longer. It is important to disturb the animals as little as possible as they are extremely fragile following surgery and will disintegrate if shaken.

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Student Surgery Sheet

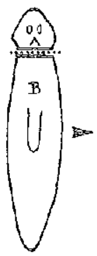

Fig. 1

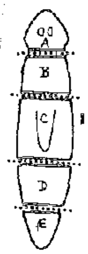

Fig. 2

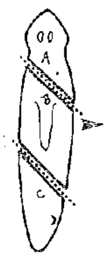

Fig. 3

Fig. 4

Fig. 5

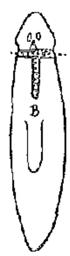

Fig. 6

Fig. 7

Fig. 8

Fig. 9

I
Notes on Galen's Physiology[1]

The following is a brief description of some of Galen's notions about nutrition'and respiration. It is made necessary by Harvey's constant reference to Galen's views on these matters, and because Galen never collected his opinions into any single text. Although this is inconvenient for us, it makes perfect sense once one realizes that his principles and categories are not those of modern physiology. Consequently, when the opinions which he expresses in various places in his books are brought together as if they comprised a doctrine of the blood and its functions, they reveal a number of inconsistencies which he may never have been aware of. Such a compilation of opinions is precisely what Harvey undertakes in his book, admitting by this that the refutation of Galen is a *necessary* beginning of his work.

Nutrition

Digested food from the stomach and intestines flows through the hepaticportal system into the liver where it is made into blood.[2] Blood is, for Galen, the food of the organism. Sometimes--but not consistently--Galen attributes the nutritive capacity of this blood to a species of "spirit" (pneuma).[3] It is carried by the veins throughout the body where it is consumed.[4] The liver is thus an organ of supreme importance. Blood is manufactured in it and the veins originate in its as its means of distributing blood throughout the body.

From the liver blood is sent to the posterior vena cava via the hepatic vein. Part of it then goes to nourish the posterior parts of the body. The rest is carried to the right atrium from which another part goes to nourish the upper parts of the body via the anterior vena cava. The rest enters the right ventricle. Notice that for Galen the anterior and posterior venae cavae are essentially one vessel which merely passes through the heart and does not originate there. The atrium, for him, is part of the vein and not of the heart.[6]

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[1] These notes were originally prepared by N. Maistrellis; they have been modified and expanded here. The drawing on p. 4 was originally adapted by H. Golding from Figure 30 in Charles Singer, *A Short History ofAnatomy and Physiology from the Greeks to Harvey,* Dover Publications, 1957. (Original Title: *The Evolution of Anatomy.)*

[2] *On the Usefulness of the Parts of the Body,* IV: 2-3, cf. 7.

[3] See the discussion of "physical pneuma" below. [4] *Parts,* IV: 4-6.

[5] *Parts,* IV: 5, 9-13. [6] *Parts,* IV: 5-7.

In the right ventricle the blood is worked on by the heart. It is heated up and thinned out so as to make it appropriate food for the lungs, whose flimsy substance could not be properly nourished by the thick blood that comes directly from the liver.[7] Part of this elaborated blood is then sent to the lungs via the "artery-like vein". Notice that the right heart is an organ of nutrition.

Respiration

The rest of the blood in the right ventricle is then sent to the left ventricle through minute pores which Galen assumed to exist in the septum separating the ventricles [8] Of the blood.which went to the lungs, only some of it goes to nourish them. The rest becomes imbued with a part.of the air entering the lungs.' He calls this part "pneuma," (breath or spirit), but it is associated with a higher gradation of spirit than that which belongs to the liver.[10] This pneumaimpregnated blood now flows to the left atrium through the "vein-like artery," and thence to the left ventricle. There it becomes mixed with the blood which had entered through the pores in the septum. This mixture of blood and pneuma is then "cooked" in the left ventricle to form arterial blood which is cooler and lighter than venous blood." The hot and smoky by-products of this elaboration leave the heart via the vein-like artery, and are expelled by the lungs. [12] This arterial blood is then distributed throughout the body. The lungs therefore have two distinct functions: they are the means by which pneuma enters the body; and they are necessary for cooling the heart and expelling the by-products of its activity.

The *Pneuma*

The role which the pneuma plays in the maintenance of the organism is never very clearly described by Galen. It is the obscurest part of his thought. According to the usual account,[13] there are for Galen three kinds of pneuma. The least exalted of these is "physical" or "natural" pneuma; this is a nutritive capacity that is bestowed upon blood when the latter is brought to its finished state in the liver. The next gradation of pneuma arises in the left ventricle of the

7 *Pam,* VI: 10.

8 *On the Natural Faculties,* III: 15. [9] *Parts,* VI: 2.

10 See the discussing of "vital pneuma" below. [11] *Cf. Parts, VI: 10.*

12 *Parts,* VI: 2.

13 Charles Singer,A *Shon History ofAnatomy and Physiology from the Greeks to Harvey,* Dover Publications, 1957, pp. 58-61. (Original Title: *The Evolution ofAnatomy.*)
A much simplified version is offered in Helen Rapson, *The Circulation of the Blood,* London: Frederick Muller, Limited 1982.

I

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heart through the mixing and cooking processes described above -- this is "vital pneuma". Finally there is "psychic" or "animal" pneuma, which (perhaps) originates through an action upon arterial blood in the brain and which is subsequently distributed throughout the body by means of the nerves, which are thought to be hollow. Thus, according to Galen's views, every tissue in the body receives physical pneuma from the veins, vital pnéuma from the arteries, and psychic pneuma from the nerves.

In certain places in his writings Galen speaks of the pneuma as if it were a substance permeating the body, and responsible for the powers of specific parts. In other places he seems to ignore the pneuma. Harvey criticizes him sharply for inconsistencies like this one..

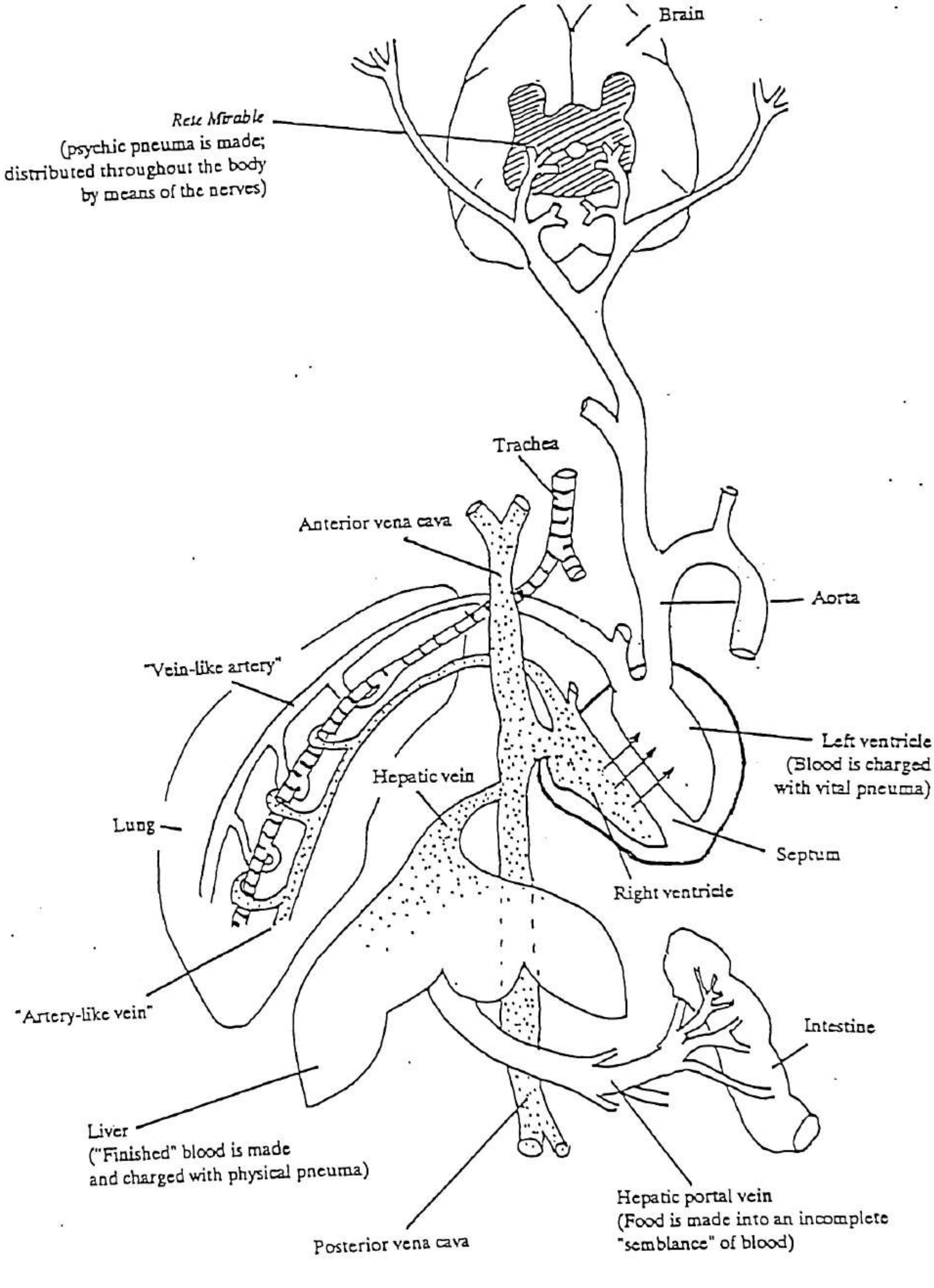
For those who would like to explore further Galen's writings on these topics, the following works will be useful:

On Anatomical Procedures, trans. Charles Singer, Oxford University Press 1956. Especially pp. 172-200; an excerpt follows later in this panphlet.

On the Natural Faculties, Translated by Arthur John Brock, M.D., Loeb Classical Library, 1916. Especially chapters XIII-XV.

On the Usefulness of the Parts of the Body, trans. Margaret Talmadge May, Cornell University Press, 1968 Especially Book VI, Chaps. 1-18, 20.

I



Galen's Physiological System

II

From Galen: *On Anatomical Procedures,* Book VII[14]

Chapter 4

That my account may be lucid, I shall now explain the names which we have to employ. As all designate the pulsating organ KARDIA [heart], so they call each pulsating vessel ARTERIA.

It is easy to discern the arteries throughout the body by their pulsation and by their continuity with the Great Artery. But it is impossible to discern by the senses the pulsation of those in the lungs [i.e., branches of the "vein-like artery"]. In spite of this one might guess at [their nature] from their continuity with the left ventricle of the heart.[15] Nevertheless, some think they have not only a suspicion, or a well-founded expectation, but exact knowledge of their activity. The two schools claim knowledge in different ways, arising from different opinions.

The one school, following Erasistratus, assumes that the arteries in the lungs [i.e., the "vein-like arteries"] are empty of blood like the other arteries.[16] They hold that at each diastole of the heart the PNEUMA is drawn through them out of the lungs [into the left ventricle] and by its passage the pulse is produced in all the arteries throughout the body. They are persuaded that the pulse is not produced in these [arteries] by their own action, as is that of the heart, but by their being filled with the PNEUMA passing through them. They say, too, that the heart, when it contracts, sends forth the PNEUMA to the arteries.

The other school thinks that the other arteries [in the body] as well as those in the lungs [i.e., branches of the "vein-like artery"] contract and dilate by the same power as the heart They say that the difference is that the power belongs by nature to the heart and is infused into the arteries from it.

According to the first school, if, on a living animal, you cut through all ribs on both sides and examine the lung, [you will find

14 Translated by Charles Singer, Oxford University Press 1956, pp. 175-179. The present selection is slightly emended and abridged.

15 Galen usually ignores the atria, regarding the "vein-like artery" and the vena cava as attached directly to the left and right ventricles respectively. Thus the vein-like artery is for him a vessel proceeding *from* the left ventricle. --Tr.

16 Erasistratus held that the arteries in general contain only pneuma, and not blood. It was in refutation of this view that Galen wrote his tract *Whether Blood is Naturally Contained in theArteries.* The three following sentences summarize the Erasistratcan theory of · the pncuma.

that] so long as the rough arteries [i.e., the bronchial tree][17] convey PNEUMA to the smooth arteries [vein-like arteries] that come from the heart, you will find a kind of pulse in them, but when they [the bronchial tree) are empty there will be none.

According to the second school, while the animal lives not only do the arteries in the moving part of the lungs go on pulsating but also those in the exposed part.

As for the received opinions of the experts, I have explained what consequences follow. But since in this work I am not concerned with passing judgement on opinions, but with the phenomena revealed by dissection, I shall try to guide you to the facts. Therefore make a straight incision in a downward direction along the length of the animal where the ribs are cartilaginous. With a single stroke of a large scalpel you can sever all the ribs below the first.Spare that rib for fear of the haemorrhage that might follow your wounding of the vessels under it. If you have succeeded so far, strip off the membrane from the lungs as fast as possible. Then with your fingers remove the flesh between th [pulmonary] vessels and lay them bare. Try to see and feel if any of the vessels in the lung has a pulse. Anything you find with a pulse you may regard as an artery. But unless its movements be clearly distinguished you should not call a vessel an artery, whether it spring from the left ventricle or the right, whatever some of the anatomists may say. They differ from one another over this terminology, for some declare that the vessel springing from the left ventricle is an artery or vein, others that springing from the right. A better course is theirs who refuse to call either of these "artery" or "vein" simply, but modify this hasty ascription by calling them "artery-like vein" or "vein-like artery". In fact four names have been given to two vessels by anatomical experts.

I follow what I take to be the better view of those who call the vessel springing from the left ventricle of the heart "vein-like artery"'S and that springing. from the right ventricle "artery-like vein". I think it preferable (since we cannot distinguish them clearly by the pulse) to call the vessel containing PNEUMA an "artery" but, since it has the covering of a vein, to add "vein-like". So to the other I give the name of "vein" from its function, but since its substance is that of an artery, I add "arterial".

It would be best, as I said, to distinguish these vessels by the presence or absence of a pulse. But as that is not clearly discernible by the senses, their names should be given from their

17 *Rough arteries*. This expression refers both to the trachea (windpipe) and to the bronchial tree within the lungs; compare in Chapter 6 below. Note that in the Erasistratean view, "arteries" are not blood vessels; so there is nothing improper in applying the term "arteries" to air-passages.

[18] Compare note 15 above.

communication with the two ventricles, with a qualification from their substance. Those who name them without adding a qualification pay attention to their substance only, or to their function only. By substance, the vessel springing from the right ventricle of the heart is an artery, that from the left a vein. Conversely, by function, that from the left is an artery, that from the right a vein.

Chapter 6

It is now time to detail of what substance the vessels are made.

The veins throughout the body have come into being each with a single intrinsic coat, for the membrane that sometimes surrounds them is in contact with them only where they need to be bound to certain tissues or fixed firmly and protected. The arteries have two intrinsic coats, the outer like that of the vein, the inner about five times a thick and harder. It consists of transverse fibres. The outer coat, like that of the veins, has longitudinal fibres, some slightly oblique, but none transverse. The inner, thick, hard tunic of the arteries has a woven sort of membrance on its inner surface, which can be seen in the large vessels. Some regard it as a third coat. There is no fourth intrinsic coat but, like certain of the veins, some arteries have attached to and round them in places a delicate membrane which guards or fixes them firmly or binds them to neighboring parts...

What the arteries are throughout the body, such is that vessel from the right ventricle of the heart which branches throughout the lungs. And what the veins are, such is that vessel from the left ventricle.

Thus of the three vessels linked with the lungs, the one from the left ventricle is called "vein-like artery", that from the right, "artery-like vein", and the third is the "rough artery" [trachea]. The last is made of cartilages...

The parts between the vessels in the lungs are filled up by the peculiar substance which disciples of Erasistratus call PARENCHYMA.[19] You can remove [the lungs] from the thorax and dissect them like the, heart itself, but it is not possible to realize their association with the membranes if once so removed.

[19] *Parenchyma*, "poured in beside." This passage is the origin of our modern term which did not come into use until the seventeenth century. – Tr.

Aristotle: *On Generation and Corruption*[1]

Book II, end of chapter 1, 2–4, 8

§1. . . . Our own doctrine is that although there is a matter of the perceptible bodies (a matter out of which the so-called elements come-to-be), it has no separate existence, but is always bound up with a contrariety. A more precise account of these presuppositions[2] has been given in another work;[3] we must, however, give a detailed explanation of the primary bodies as well, since they too are similarly derived from the matter. We must reckon as an originative source[4] and as primary the matter which underlies, though it is inseparable from, the contrary qualities; for the hot is not matter for the cold nor the cold for the hot, but the *substratum* is matter for them both. We therefore have to recognize three originative sources:[5] *firstly* that which potentially perceptible body, *secondly* the contrarieties (I mean, e.g., heat and cold), and *thirdly* Fire, Water, and the like. Only thirdly, however:[6] for these bodies change into one another (they are not immutable as Empedocles and other thinkers assert, since alteration would then have been impossible), whereas the contrarieties do not change.

Nevertheless, even so the question remains: What sorts of contrarieties, and how many of them, are to be accounted originative sources of body? For all the other thinkers assume and use them without explaining why they are *these* or why they are just *so many.*

§2. Since, then, we are looking for originative sources of perceptible body; and since perceptible is equivalent to tangible, and tangible is that of which the perception is touch, it is clear that not all the contrarieties constitute forms and originative sources of body, but only those which correspond to touch. For it is in accordance with a contrariety—a contrariety, moreover, of *tangible* qualities—that the primary bodies are differentiated. That is why neither whiteness and blackness, nor sweetness and bitterness, nor similarly any quality belonging to[7] the other perceptible contrarieties either, constitutes an element. And yet vision is prior to touch, so that its object also is prior to the object of touch.[8] The object of vision, however, is a quality of tangible body not *qua* tangible, but *qua* something else—*qua*

[1] Translated by H. H. Joachim, (1922). Differences from the revised version in the Oxford Complete Works are noted in the footnotes that follow. Changes in punctuation are made but go unnoted.

[2] "these presuppositions" replaced by "this".

[3] Footnote added: "See *Physics* I.6–9".

[4] "originative source(s)" replaced by "principle(s)" throughout.

[5] "Thus as principles we have".

[6] "Only thirdly, however:" deleted.

[7] "nor similarly any of the".

[8] "to the object of touch" deleted.

something which may well be naturally prior to the object of touch.[1]

Accordingly, we must segregate the tangible differences and contrarieties, and distinguish which amongst them are primary. Contrarieties correlative to touch are the following: hot-cold, dry-moist, heavy-light, hard-soft, viscous-brittle, rough-smooth, coarse-fine. Of these (i)[2] heavy and light are neither active nor susceptible. Things are not called heavy and light because they act upon, or suffer action from, other things. But the elements must be reciprocally active and susceptible, since they combine and are transformed into one another. On the other hand (ii), hot and cold, and dry and moist, are terms, of which the first pair implies *power to act* and the second pair *susceptibility.* Hot is that which associates things of the same kind (for dissociating, which people attribute to Fire as its function, *is* associating things of the same class, since its effect is to eliminate what is foreign), while cold is that which brings together, i.e., associates, homogeneous and heterogeneous things alike. And moist is that which, being readily adaptable in shape, is not determinable by any limit of its own; while dry is that which is readily determinable by its own limit, but not readily adaptable in shape.

From moist and dry[3] are derived (iii) the fine and coarse, viscous and brittle, hard and soft, and the remaining tangible[4] differences. For (a) since the moist has no determinate shape, but is readily adaptable and follows the outline of that which is in contact with it, it is characteristic of it to be such as to fill up. Now the fine is such as to fill up. For the fine consists of subtle particles; but that which consists of small particles is such as to fill up, inasmuch as it is in contact whole with whole—and the fine exhibits this character in a superlative degree. Hence it is evident that the fine derives from the moist, while the coarse derives from the dry. Again (b) the viscous derives from the moist: for the viscous (e.g. oil) is a moist thing modified in a certain way. The brittle, on the other hand, derives from the dry: for brittle is that which is *completely* dry—so completely, that its solidification has actually been[5] due to failure of moisture. Further (c) the soft derives from the moist. For soft is that which yields to pressure[6] by retiring into itself, though it does not yield by total displacement[7] as the moist does—which explains why the moist is not soft, although the soft derives from the moist. The hard, on the other hand, derives from the dry; for hard is that which is solidified, and the solidified is dry.

[1] "—*qua* . . . touch." replaced by "—even if it *is* naturally prior."
[2] All enumerations in the text, by number or letter, are deleted.
[3] "From these".
[4] "tangible" deleted.
[5] "so completely, that it has actually been solidified".
[6] 'to pressure' deleted.
[7] "though it does change position,".

The terms ‘dry’ and ‘moist’ have more senses than one. For the damp, as well as the moist, is opposed to the dry: and again the solidified, as well as the dry, is opposed to the moist. But all these qualities[1] derive from the dry and moist we mentioned first. For (i) the dry is opposed to the damp; i.e.[2] the damp is that which has foreign moisture on its surface (sodden being that which is penetrated to its core), while dry is that which has lost foreign moisture. Hence it is evident that the damp will derive from the moist, and the dry which is opposed to it will derive from the primary dry. Again (ii) the moist and the solidified derive in the same way from the primary pair. For moist is that which contains moisture *of its own* deep within it (sodden being that which is deeply penetrated by[3] *foreign* mosture), whereas solidified is that which has lost this inner moisture. Hence these too derive from the primary pair, the solidified from the dry and the liquefiable from the moist.[4]

It is clear, then, that all the other differences reduce to the first four, but that these admit of no further reduction. For the hot is not *essentially* moist or dry, nor the moist *essentially* hot or cold: nor are the cold and the dry derivative forms, either of one another or of the hot and the moist. Hence these must be four.

§3. The elementary qualities[5] are four, and any four terms can be combined in six couples. Contraries, however, refuse to be coupled; for it is impossible for the same thing to be hot and cold, or moist and dry. Hence it is evident that the couplings of the elementary qualities will be four: hot with dry and moist with hot, and again cold with dry and cold with moist. And these four couples have attached themselves 330 b1 to the *apparently* simple bodies (Fire, Air, Water, and Earth) in a manner consonant with theory. For Fire is hot and dry, whereas Air is hot and moist (Air being a sort of aqueous[6] vapour); and Water is cold and moist, while Earth is cold and dry. Thus the differences are reasonably distributed among the primary bodies, and the number of the latter is consonant with theory. For all who make the simple bodies elements postulate either one, or two, or three, or four. Now (i) those who assert there is *one* only, and then generate everything else by condensation and rarefaction, are in effect making their ’originative sources’ two, viz. the rare and the dense, or rather the hot and the cold; for it is these which are the moulding forces, while the one underlies them as a[7] matter. But (ii) those who postulate *two* from the start—as Parmenides postulated Fire and Earth—make the intermediates

[1] “qualities” deleted.
[2] “i.e.” replaced by “and”.
[3] “that which contains”.
[4] “Hence these too derive one from the dry and the other from the moist.”
[5] “elementary qualities” replaced by “elements” throughout.
[6] “aqueous” deleted.
[7] “a” deleted.

(e.g. Air and Water) blends of these. The same course is followed (iii) by those who advocate *three*. (We may compare what Plato does in the divisions;[1] for he makes 'the middle' a blend.) Indeed, there is practically no difference between those who postulate *two* and those who postulate *three*, except that the former split the middle element into two, while the latter treat it as only one. But (iv) some advocate *four* from the start, e.g. Empedocles; yet he too draws them together so as to reduce them to *the two*, for he opposes all the others to Fire.

In fact, however, fire and air, and each of the bodies we have mentioned, are not simple, but blended.[2] The simple bodies are indeed similar in nature to them, but not identical with them. Thus the simple body corresponding to fire is such-as-fire,[3] not fire; that which corresponds to air is such-as-air;[4] and so on with the rest of them. But fire is an excess of heat, just as ice is an excess of cold. For freezing and boiling are excesses of heat and cold respectively. Assuming, therefore, that ice is a freezing of moist and cold, fire analogously will be a boiling of dry and hot—a fact, by the way,[5] which explains why nothing comes-to-be either out of ice or out of fire.

The simple bodies, since they are four, fall into two pairs which belong to the two regions, each to each: for Fire and Air are forms of the body moving towards the limit, while Earth and Water are forms of the body which moves towards the centre. Fire and Earth, moreover, are extremes and purest: Water and Air, on the contrary are intermediates and more like blends[6]. And, further, the members of either pair are contrary to those of the other, Water being contrary to Fire and Earth to Air; for the qualities constituting Water and Earth are contrary to those that constitute Fire and Air.[7] Nevertheless, since they are four, each of them is characterized *par excellence*[8] by a single quality: Earth by dry rather than by cold, Water by cold rather than by moist, Air by moist rather than by hot, and Fire by hot rather than by dry.

§4. It has been established before that the coming-to-be of the simple bodies is reciprocal. At the same time, it is manifest, even[9] on the evidence of perception, that they *do* come-to-be; for otherwise there would not have been alteration, since alteration is change in respect to the qualities of the objects of touch. Consequently, we must explain (i) what is the manner of their reciprocal transformation, and (ii) whether

[1] Footnote added: "The ancient commentators take Aristotle to be referring to Plato's 'unwritten doctrines'; Joachim thinks that the reference is to *Timaeus* 35Aff."
[2] "combined".
[3] "fire-like".
[4] "air-like".
[5] ", by the way," deleted.
[6] "more combined".
[7] "; for they are constituted from contrary qualities.".
[8] "simply"
[9] "even" deleted.

every one of them can come-to-be out of every one—or whether some can do so, but not others.

Now it is evident that all of them are by nature such as to change into one another; for coming-to-be is a change into contraries and out of contraries, and the elements all involve a contrariety in their mutual relations because their distinctive qualities are contrary. For in some of them *both* qualities are contrary—e.g. in Fire and Water, the first of these being dry and hot, and the second moist and cold; while in others *one* of the qualities (though only one)[1] is contrary—e.g. in Air and Water, the first being moist and hot, and the second moist and cold. It is evident, therefore, if we consider them in general, that every one is by nature such as to come-to-be out of every one; and when we come to consider them severally, it is not difficult to see the manner in which their transformation is effected. For, though all will result from all, both the speed and the facility of their conversion will differ in degree.

Thus (i) the process of conversion will be quick between those which have interchangeable complementary factors,[2] but slow between those which have none.[3] The reason is that it is easier for a single thing to change than for many. Air, e.g., will result from Fire if a single quality changes; for Fire, as we saw, is hot and dry while Air is hot and moist, so that there will be Air if the dry be overcome by the moist. Again, Water will result from Air if the hot be overcome by the cold; for Air, as we saw, is hot and moist while Water is cold and moist, so that, if the hot changes, there will be Water. So too, in the same manner, Earth will result from Water and Fire from Earth, since the two elements in both these couples have interchangeable complementary factors.[4] For Water is moist and cold while Earth is cold and dry—so that, if the moist be overcome, there will be Earth; and again, since Fire is dry and hot while Earth is cold and dry, Fire 331 b1
will result from Earth if the cold pass-away.

It is evident, therefore, that the coming-to-be of the simple bodies will be cyclical; and that this cyclical[5] method of transformation is the easiest, because the *consecutive* elements contain interchangeable complementary factors.[6] On the other hand (ii) the transformation of Fire into Water and of Air into Earth, and again of Water and Earth into Fire and Air respectively,[7] though possible, is more difficult because it involves the change of more qualities. For if Fire is to result from Water, both the cold and the moist must pass-away; and again,

[1] "(though only one)" deleted.
[2] "those which tally with one another,".
[3] "which do not.".
[4] "since both tally with both".
[5] "cyclical" deleted.
[6] "tally".
[7] "respectively" deleted here and below.

both the cold and the dry must pass-away if Air is to result from Earth. So, too, if Water and Earth are to result from Fire and Air respectively—both qualities[1] must change.

This second method of coming-to-be, then, takes a longer time. But (iii) if one quality in each of two elements pass-away, the transformation, though easier, is not reciprocal. Still, from Fire plus[2] Water there will result Earth and Air, and from Air plus Earth Fire and Water. For there will be Air, when the cold of the Water and the dry of the Fire have passed-away (since the hot of the latter and the moist of the former are left); whereas, when the hot of the Fire and the moist of the Water have passed-away, there will be Earth, owing to the survival of the dry of the Fire and the cold of the Water. So, too, in the same way, Fire and Water will result from Air plus Earth. For there will be Water, when the hot of the Air and the dry of the Earth have passed-away (since the moist of the former and the cold of the latter are left); whereas, when the moist of the Air and the cold of the Earth have passed-away, there will be Fire, owing to the survival of the hot of the Air and the dry of the Earth—qualities essentially[3] constitutive of Fire. Moreover, this mode of Fire's coming-to-be is confirmed by perception. For flame is *par excellence* Fire; but flame is burning smoke, and smoke consists of Air and Earth.

No transformation, however, into any of the simple[4] bodies can result from the passing-away of one elementary[5] quality in each of two elements when they are taken in their consecutive order, because either *identical* or *contrary* qualities are left in the pair—but no simple body can be formed either out of identical, or out of contrary, qualities.[6] Thus no 'simple' body would result,[7] if the dry of Fire and the moist of Air were to pass-away; for[8] the hot is left in both. On the other hand,[9] if the hot pass-away out of both, the contraries—dry and moist—are left. A similar result will occur in all the others too; for all the *consecutive* elements[10] contain one identical and one contrary quality. Hence, too, it clearly follows that, when one of the consecutive elements[11] is transformed into one, the coming-to-be is effected by the passing-away of a single quality: whereas, when two of them[12] are transformed into a third, more than one quality must 332 a1

[1] "qualities" deleted.
[2] "plus" replaced by "and" throughout.
[3] "essentially" deleted.
[4] "simple" deleted.
[5] "elementary" deleted.
[6] "left—and from them no body can be formed."
[7] This clause replaced by "E.g."
[8] "for" deleted.
[9] "and".
[10] "bodies"
[11] "of the consecutive elements" deleted.
[12] "of them" deleted.

have passed-away.

* * *

§8. All the compound bodies—all of which exist in the region belonging to the central body—are composed of all the simple bodies. For they all contain Earth because every simple body is to be found specially and most abundantly in its own place. And they all contain Water because (a) the compound must possess a definite outline and Water, alone of the simple bodies, is readily adaptable in shape; 334 b31
moreover (b) Earth has no power of cohesion without the moist. On 335 a1
the contrary, the moist is what holds it together; for it would fall to pieces if the moist were eliminated from it completely.

They contain Earth and Water, then, for the reasons we have given; and they contain Air and Fire, because these are contrary to Earth and Water (Earth being contrary to Air and Water to Fire, in so far as one Substance can be contrary to another). Now all compounds presuppose in their coming-to-be constituents which are contrary to one another;[1] and in all compounds there is contained one set of the contrasted extremes.[2] Hence the other set must be contained in them also,[3] so that every compound will include all the simple bodies.

Additional evidence seems to be furnished by the food each compound takes. For all of them are fed by substances which are the same as their constituents,[4] and all of them are fed by more substances[5] than one. Indeed, even the[6] plants, though it might be thought they are fed by one substance[7] only, viz. by Water, are fed by more than one; for Earth has been mixed with the Water. That is why farmers too endeavour to mix before watering. Although food is akin to the matter, that which is fed is the figure—i.e. the form—taken along with the matter. This fact enables us to understand why,[8] whereas all the simple bodies come-to-be out of one another, Fire is the only one of them which (as our predecessors also assert) is fed. For Fire alone—or more than all the rest—is akin to the form because it tends by nature to be borne towards the limit. Now each of them naturally tends to be borne towards its own place; but the figure—i.e. the form—Of them all is at the limits.

Thus we have explained that all the compound[9] bodies are composed of all the simple bodies.

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[1] "Now comings-to-be result from contraries,".
[2] "and one pair of the contrary extremes is present;".
[3] "hence the other pair must also be present,".
[4] "fed by what they are constituted from,".
[5] "things".
[6] "the" deleted.
[7] "thing".
[8] "Hence it is reasonable that,".
[9] "the compound" deleted.

The Golden Crown as described in *The Ten Books on Architecture* by Marcus Vitruvius Pollio (c. first century BC)—Book IX, Introduction; translated by M.H. Morgan

9. In the case of Archimedes, although he made many wonderful discoveries of diverse kinds, yet of them all, the following, which I shall relate, seems to have been the result of a boundless ingenuity. Hiero, after gaining the royal power in Syracuse, resolved, as a consequence of his successful exploits, to place in a certain temple a golden crown which he had vowed to the immortal gods. He contracted for its making at a fixed price, and weighed out a precise amount of gold to the contractor. At the appointed time the latter delivered to the king's satisfaction an exquisitely finished piece of handiwork, and it appeared that in weight the crown corresponded precisely to what the gold had weighed.

10. But afterwards a charge was made that gold had been abstracted and an equivalent weight of silver had been added in the manufacture of the crown. Hiero, thinking it an outrage that he had been tricked, and yet not knowing how to detect the theft, requested Archimedes to consider the matter. The latter, while the case was still on his mind, happened to go to the bath, and on getting into a tub observed that the more his body sank into it the more water ran out over the tub. As this pointed out the way to explain the case in question, he jumped out of the tub and rushed home naked, crying with a loud voice that he had found what he was seeking; for he as he ran he shouted repeatedly in Greek, "Εὕρηκα, εὕρηκα" [= "Eureka, eureka" = "I have found (it), I have found (it)"].

11. Taking this as the beginning of his discovery, it is said that he made two masses of the same weight as the crown, one of gold and the other of silver. After making them he filled a large vessel with water to the very brim, and dropped the mass of silver into it. As much water ran out as was equal in bulk to that of the silver sunk in the vessel. Then, taking out the mass, he poured back the lost quantity of water, using a pint measure, until it was level with the brim as it had been before. Thus he found the weight of silver corresponding to a definite quantity of water.

12. After this experiment, he likewise dropped the mass of gold into the full vessel and, on taking it out and measuring as before, found that not so much water was lost, but a smaller quantity: namely, as much less as a mass of gold lacks in bulk compared to a mass of silver of the same weight. Finally, filling the vessel again and dropping the crown itself into the same quantity of water, he found that more water ran over the crown than for the mass of gold of the same weight. Hence, reasoning from the fact that more water was lost in the case of the crown than in that of the mass, he detected the mixing of silver with the gold, and made the theft of the contractor perfectly clear.

THE LITTLE BALANCE

Galileo Galilei

In 1586 at the age of 22, Galileo (1564-1642) wrote a short treatise entitled *La Bilancetta* ("The Little Balance"). He was skeptical of Vitruvius's account of how Archimedes determined the fraud in Hiero's crown and in this treatise presented his own theory based on Archimedes' Law of the Lever and Law of Buoyancy. His presentation included a description of a hydrostatic balance that determined the precise composition of an alloy of two metals.

The present translation is by Jack V. Wales, Jr., with some edits by William Donahue.

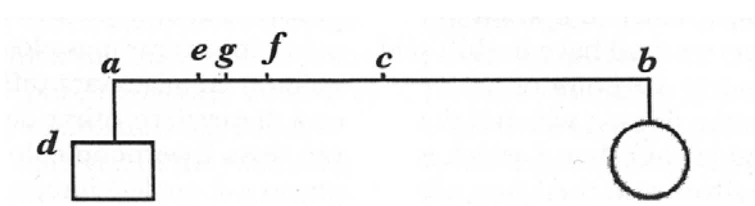
[1.1]As is indeed well known to one who takes care to read the ancient writers, Archimedes found the goldsmith's theft in Hiero's crown of gold, but still the method which that great man must have used in this discovery seems to me to have been unknown until now. [1.2]As to the belief that he proceeded, as is written by some, by putting the crown in water, having first so put equally as much of purest gold and of silver separately, and that from differences in which water was made to rise or spill over he came into knowledge of the mixture of gold with silver of which the crown was composed, the thing appears, so to speak, very crude and far from exquisiteness; [1.3]and it becomes even more so to those who will have read and understood the subtlest inventions of so divine a man among his writings, from which one only too clearly understands by how much all other minds are inferior to that of Archimedes, and what small hope there might be for anyone of ever being able to find things similar to those he found. [1.4]Well, I believe that, word having spread of Archimedes' discovery of that theft by means of water, there might have been a writer of the times who left a written record of the fact; [1.5]and that that writer, by way of adding something to the little that he had understood of the news, might have said that Archimedes made use of water in the way which has since been universally believed. [1.6]But I, knowing that that method was altogether fallacious and devoid of such exactness as is required in mathematical things, have often pondered in what manner, by means of water, one might be able exquisitely to find the mixture of two metals; [1.7]and finally, after having with diligence reviewed that which Archimedes demonstrates in his books *Of the things that rest in water* and *Of the things that weigh* (pesano)[1] *equally*, there came to my mind a method that most exquisitely resolves the problem. [1.8]I believe this method to be the very one that Archimedes used, since, besides being most exact, it also depends on demonstrations found by Archimedes himself.

[2.1]This method is by means of a balance, whose construction and use will be put here presently, after such as is needed for a certain understanding shall have been laid out. [2.2]One must first know that solid bodies that sink in water weigh when in water by as much less than when in air as the heaviness in air of as much water in bulk as the body. [2.3]This was demonstrated by Archimedes, [2.4]but because his demonstration is very involved, so as not to have gone on at too much length, I will leave it aside, and I will demonstrate it by other means. [2.5]Let us consider, then, that putting, for example, a ball

[1] The titles of these works of Archimedes are translations of Galileo's Italian names for them. There is no suitable English equivalent to the Italian *pesare* and its variants. For example, in this case, Archimedes refers to things that balance each other, though they may not be equally heavy. Throughout this translation, wherever this word appears in the Italian, it is translated using "weigh," even if this is at odds with English usage, so as to follow Galileo's usage as nearly as possible.

of gold in water, if the ball were water, it would not weigh at all because water within water does not move up or down. [2.6]It remains therefore that in water this ball of gold weighs by as much as the heaviness of the gold exceeds the heaviness of the water; [2.7]and the like is to be understood of the other metals; [2.8]and because metals are different from each other in heaviness, their heaviness in water will decrease in different proportions. [2.9]Such as, for example, let us posit that gold weighs twenty times as much as water; [2.10]it is evident from what has been said that gold will weigh less in water than in air by the twentieth part of its total heaviness. [2.11]Let us suppose next that silver, for it is less heavy than gold, weighs 12 times more than water; [2.12]this, weighed in water, will decrease in heaviness by the twelfth part. [2.13]Thus the heaviness of gold decreases less in water than that of silver, since that decreases by a twentieth and this by a twelfth.

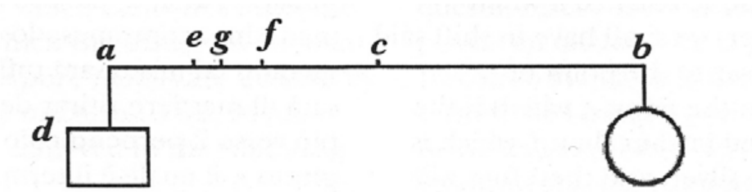
[3.1]If therefore on an exquisite balance we should hang (*appenderemo*) a metal, and on the other arm a counterpoise (*contrapeso*) that weighs equally with the said metal in air, [3.2]and if then we should immerse the metal in water, leaving the counterpoise in air, [3.3]then in order for said counterpoise to be equivalent to the metal, it would be necessary to withdraw it toward the upright. [3.4]As, for example, let there be the balance *ab*, the upright of it *c*, [3.5]and a mass of some metal hung (*appesa*) at *b*, counterpoised by the weight *d*. [3.6]The weight *b* having been put in water, the weight *d* at *a* would weigh more. [3.7]In order that it weigh equally, we should withdraw it toward the upright *c*, as, *e.g.*, to *e*; [3.8]and as many times as the distance *ca* will exceed the distance *ae*, that many times will the metal weigh more than water.



[4.1]Let us then posit that the weight at *b* be gold, and that when it is weighed while in water, the counterpoise *d* goes back to *e*; [4.2]and then, doing the same with finest silver, that its counterpoise, when you will weigh it while it is in water, goes back to *f*: [4.3]this will be the closer point to *c*, so that the experiment will show silver to be less heavy than gold; [4.4]and the difference there is from the distance *af* to the distance *ae* will be the same as the difference between the heaviness of gold and that of silver. [4.5]But if we should have a mixture of gold and silver, it is clear that, by participating in silver, it will weigh less than the pure gold, and, by participating in gold, it will weigh more than the pure silver; [4.6]and so, having weighed it in air, and wanting the same counterpoise to counterweigh it when the mixture will be immersed in water, one will need to retire said counterpoise more toward the upright *c* than is the point *e*, which is the terminus for gold, and likewise more distant from *c* than is the point *f*, which is the terminus for pure silver; [4.7]but then it will fall between the termini *e*, *f*, and from the proportion in which the distance *ef* will be divided one will have exquisitely the proportion of the two metals which compose this mixture. [4.8]As, for example, let us take it that the mixture of gold and silver be at *b*, counterweighed in air by *d*; [4.9]while the counterpoise, when the mixture be placed in water, returns to *g*. [4.10]I say now that the gold and silver which compose this mixture will have between them the same proportion as the distances *fg*, *ge*. [4.11]But we must be aware that the distance *gf*, terminating in the mark for silver, will denote to us the quantity of gold, and the distance *ge*, terminating in the mark for gold, will demonstrate to us the quantity of silver, [4.12]so that if *fg* should return double of *ge*, the mixture would be two of gold and one of silver. [4.13]And with the same order proceeding in the examination of other mixtures, one will find exquisitely the amounts of the simple metals.

[5.1]To make the balance, then, take a straightedge at least two arms long, and the longer it is, the more exact will be the instrument; and let it be divided in the middle, and let the upright be put there, [5.2]and then let the arms be adjusted so that they are in equilibrium, by thinning the one which may have weighed more, [5.3]and on one of the arms mark the termini to which return the counterpoises of the simple metals when they have been weighed while in water, being careful to weigh the purest metals that can be found. [5.4]This being arranged, there remains finding a method by which one might easily obtain the proportions according to which the distances between the termini of the pure metals will be divided by the marks of the mixtures. [5.5]That, in my opinion, will be accomplished in the following way:

[6.1]Over the termini of the simple metals let there be wound a single strand of extremely thin steel wire, [6.2]and around the intervals between the termini wind an extremely thin strand of pure brass; [6.3]and these distances will be divided into many equal particles. [6.4]As, for example, around the termini *e, f* I wind 2 single wires of steel (in order to distinguish them from brass); [6.5]and then I go about filling all the space between *e, f* by wrapping it with an extremely thin wire of brass, by which I will divide the space *ef* into many equal particles. [6.6]Then, when I want to know the proportion there is between *fg* and *ge*, I will count the wires *fg* and the wires *ge*, and, finding the wires *fg* to be 40 and the *ge* to be, for example, 21, I will say there to be in the mixture 40 of gold and 21 of silver.



[7.1]But here, by way of warning, is a difficulty that arises in the counting: [7.2]those wires being extremely thin, as is required for exquisiteness, it is not possible to count them visually, since in such small spaces the eye is dazzled. [7.3]Therefore, to count them with ease, let one obtain an extremely sharp stiletto, with which one passes slowly slowly over said wires; [7.4]so that, partly through hearing, partly through the hand encountering an obstacle at each wire, the number of wires will be easily said: [7.5]from which number, as I said above, one has the exquisite quantity of the simples of which the mixture is composed, [7.6]being careful however, that the simples will answer contrarily to the distances, [7.7]as, for example, in a mixture of gold and silver, the wires that will be towards the terminus of silver will give us the quantity of gold, and those which will be towards the terminus of gold will demonstrate to us the quantity of silver; [7.8]and the same is to be understood of the other mixtures.

On the Theory of Scales of Measurement

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Source: *Science*, Jun. 7, 1946, New Series, Vol. 103, No. 2684 (Jun. 7, 1946), pp. 677-680
Published by: American Association for the Advancement of Science
Stable URL: https://www.jstor.org/stable/1671815

SCIENCE

Vol. 103, No. 2684 Friday, June 7, 1946

On the Theory of Scales of Measurement

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FOR SEVEN YEARS A COMMITTEE of the British Association for the Advancement of Science debated the problem of measurement. Appointed in 1932 to represent Section A (Mathematical and Physical Sciences) and Section J (Psychology), the committee was instructed to consider and report upon the possibility of "quantitative estimates of sensory events"—meaning simply: Is it possible to measure human sensation? Deliberation led only to disagreement, mainly about what is meant by the term measurement. An interim report in 1938 found one member complaining that his colleagues "came out by that same door as they went in," and in order to have another try at agreement, the committee begged to be continued for another year.

For its final report (1940) the committee chose a common bone for its contentions, directing its arguments at a concrete example of a sensory scale. This was the Sone scale of loudness (S. S. Stevens and H. Davis. *Hearing*. New York: Wiley, 1938), which purports to measure the subjective magnitude of an auditory sensation against a scale having the formal properties of other basic scales, such as those used to measure length and weight. Again the 19 members of the committee came out by the routes they entered, and their views ranged widely between two extremes. One member submitted "that any law purporting to express a quantitative relation between sensation intensity and stimulus intensity is not merely false but is in fact meaningless unless and until a meaning can be given to the concept of addition as applied to sensation" (Final Report, p. 245).

It is plain from this and from other statements by the committee that the real issue is the meaning of measurement. This, to be sure, is a semantic issue, but one susceptible of orderly discussion. Perhaps agreement can better be achieved if we recognize that measurement exists in a variety of forms and that scales of measurement fall into certain definite classes. These classes are determined both by the empirical operations invoked in the process of "measuring" and by the formal (mathematical) properties of the scales. Furthermore—and this is of great concern to several of the sciences—the statistical manipulations that can legitimately be applied to empirical data depend upon the type of scale against which the data are ordered.

A Classification of Scales of Measurement

Paraphrasing N. R. Campbell (Final Report, p. 340), we may say that measurement, in the broadest sense, is defined as the assignment of numerals to objects or events according to rules. The fact that numerals can be assigned under different rules leads to different kinds of scales and different kinds of measurement. The problem then becomes that of making explicit (a) the various rules for the assignment of numerals, (b) the mathematical properties (or group structure) of the resulting scales, and (c) the statistical operations applicable to measurements made with each type of scale.

Scales are possible in the first place only because there is a certain isomorphism between what we can do with the aspects of objects and the properties of the numeral series. In dealing with the aspects of objects we invoke empirical operations for determining equality (classifying), for rank-ordering, and for determining when differences and when ratios between the aspects of objects are equal. The conventional series of numerals yields to analogous operations: We can identify the members of a numeral series and classify them. We know their order as given by convention. We can determine equal differences, as $8-6=4-2$, and equal ratios, as $8/4=6/3$. The isomorphism between these properties of the numeral series and certain empirical operations which we perform with objects permits the use of the series as a *model* to represent aspects of the empirical world.

The type of scale achieved depends upon the character of the basic empirical operations performed. These operations are limited ordinarily by the nature of the thing being scaled and by our choice of procedures, but, once selected, the operations determine that there will eventuate one or another of the scales listed in Table 1.[1]

The decision to discard the scale names commonly encountered in writings on measurement is based on the ambiguity of such terms as "intensive" and "extensive." Both ordinal and interval scales have at times been called intensive, and both interval and ratio scales have sometimes been labeled extensive.

TABLE 1

Scale	Basic Empirical Operations	Mathematical Group Structure	Permissible Statistics (invariantive)
NOMINAL	Determination of equality	*Permutation group* $x' = f(x)$ $f(x)$ means any one-to-one substitution	Number of cases Mode Contingency correlation
ORDINAL	Determination of greater or less	*Isotonic group* $x' = f(x)$ $f(x)$ means any monotonic increasing function	Median Percentiles
INTERVAL	Determination of equality of intervals or differences	*General linear group* $x' = ax + b$	Mean Standard deviation Rank-order correlation Product-moment correlation
RATIO	Determination of equality of ratios	*Similarity group* $x' = ax$	Coefficient of variation

It will be noted that the column listing the basic operations needed to create each type of scale is cumulative: to an operation listed opposite a particular scale must be added all those operations preceding it. Thus, an interval scale can be erected only provided we have an operation for determining equality of intervals, for determining greater or less, and for determining equality (not greater and not less). To these operations must be added a method for ascertaining equality of ratios if a ratio scale is to be achieved.

In the column which records the group structure of each scale are listed the mathematical transformations which leave the scale-form invariant. Thus, any numeral, x, on a scale can be replaced by another numeral, x', where x' is the function of x listed in this column. Each mathematical group in the column is contained in the group immediately above it.

The last column presents examples of the type of statistical operations appropriate to each scale. This column is cumulative in that *all* statistics listed are admissible for data scaled against a ratio scale. The criterion for the appropriateness of a statistic is *invariance* under the transformations in Column 3. Thus, the case that stands at the median (mid-point) of a distribution maintains its position under all transformations which preserve order (isotonic group), but an item located at the mean remains at the mean only under transformations as restricted as those of the linear group. The ratio expressed by the coefficient of variation remains invariant only under the similarity transformation (multiplication by a constant). (The rank-order correlation coefficient is usually deemed appropriate to an ordinal scale, but actually this statistic assumes equal intervals between successive ranks and therefore calls for an interval scale.)

Let us now consider each scale in turn.

NOMINAL SCALE

The *nominal scale* represents the most unrestricted assignment of numerals. The numerals are used only as labels or type numbers, and words or letters would serve as well. Two types of nominal assignments are sometimes distinguished, as illustrated (a) by the 'numbering' of football players for the identification of the individuals, and (b) by the 'numbering' of types or classes, where each member of a class is assigned the same numeral. Actually, the first is a special case of the second, for when we label our football players we are dealing with unit classes of one member each. Since the purpose is just as well served when any two designating numerals are interchanged, this scale form remains invariant under the general substitution or permutation group (sometimes called the symmetric group of transformations). The only statistic relevant to nominal scales of Type A is the number of cases, e.g. the number of players assigned numerals. But once classes containing several individuals have

[1] A classification essentially equivalent to that contained in this table was presented before the International Congress for the Unity of Science, September 1941. The writer is indebted to the late Prof. G. D. Birkhoff for a stimulating discussion which led to the completion of the table in essentially its present form.

been formed (Type B), we can determine the most numerous class (the mode), and under certain conditions we can test, by the contingency methods, hypotheses regarding the distribution of cases among the classes.

The nominal scale is a primitive form, and quite naturally there are many who will urge that it is absurd to attribute to this process of assigning numerals the dignity implied by the term measurement. Certainly there can be no quarrel with this objection, for the naming of things is an arbitrary business. However we christen it, the use of numerals as names for classes is an example of the "assignment of numerals according to rule." The rule is: Do not assign the same numeral to different classes or different numerals to the same class. Beyond that, anything goes with the nominal scale.

Ordinal Scale

The *ordinal scale* arises from the operation of rank-ordering. Since any 'order-preserving' transformation will leave the scale form invariant, this scale has the structure of what may be called the isotonic or order-preserving group. A classic example of an ordinal scale is the scale of hardness of minerals. Other instances are found among scales of intelligence, personality traits, grade or quality of leather, etc.

As a matter of fact, most of the scales used widely and effectively by psychologists are ordinal scales. In the strictest propriety the ordinary statistics involving means and standard deviations ought not to be used with these scales, for these statistics imply a knowledge of something more than the relative rank-order of data. On the other hand, for this 'illegal' statisticizing there can be invoked a kind of pragmatic sanction: In numerous instances it leads to fruitful results. While the outlawing of this procedure would probably serve no good purpose, it is proper to point out that means and standard deviations computed on an ordinal scale are in error to the extent that the successive intervals on the scale are unequal in size. When only the rank-order of data is known, we should proceed cautiously with our statistics, and especially with the conclusions we draw from them.

Even in applying those statistics that are normally appropriate for ordinal scales, we sometimes find rigor compromised. Thus, although it is indicated in Table 1 that percentile measures may be applied to rank-ordered data, it should be pointed out that the customary procedure of assigning a value to a percentile by interpolating linearly within a class interval is, in all strictness, wholly out of bounds. Likewise, it is not strictly proper to determine the mid-point of a class interval by linear interpolation, because the linearity of an ordinal scale is precisely the property which is open to question.

Interval Scale

With the *interval scale* we come to a form that is "quantitative" in the ordinary sense of the word. Almost all the usual statistical measures are applicable here, unless they are the kinds that imply a knowledge of a 'true' zero point. The zero point on an interval scale is a matter of convention or convenience, as is shown by the fact that the scale form remains invariant when a constant is added.

This point is illustrated by our two scales of temperature, Centigrade and Fahrenheit. Equal intervals of temperature are scaled off by noting equal volumes of expansion; an arbitrary zero is agreed upon for each scale; and a numerical value on one of the scales is transformed into a value on the other by means of an equation of the form $x' = ax + b$. Our scales of time offer a similar example. Dates on one calendar are transformed to those on another by way of this same equation. On these scales, of course, it is meaningless to say that one value is twice or some other proportion greater than another.

Periods of time, however, can be measured on ratio scales and one period may be correctly defined as double another. The same is probably true of temperature measured on the so-called Absolute Scale.

Most psychological measurement aspires to create interval scales, and it sometimes succeeds. The problem usually is to devise operations for equalizing the units of the scales—a problem not always easy of solution but one for which there are several possible modes of attack. Only occasionally is there concern for the location of a 'true' zero point, because the human attributes measured by psychologists usually exist in a positive degree that is large compared with the range of its variation. In this respect these attributes are analogous to temperature as it is encountered in everyday life. Intelligence, for example, is usefully assessed on ordinal scales which try to approximate interval scales, and it is not necessary to define what zero intelligence would mean.

Ratio Scale

Ratio scales are those most commonly encountered in physics and are possible only when there exist operations for determining all four relations: equality, rank-order, equality of intervals, and equality of ratios. Once such a scale is erected, its numerical values can be transformed (as from inches to feet) only by multiplying each value by a constant. An absolute zero is always implied, even though the zero value on some scales (e.g. Absolute Temperature) may never be produced. All types of statistical measures are applicable to ratio scales, and only with these scales may we properly indulge in logarithmic transformations such as are involved in the use of decibels.

Foremost among the ratio scales is the scale of number itself—cardinal number—the scale we use when we count such things as eggs, pennies, and apples. This scale of the numerosity of aggregates is so basic and so common that it is ordinarily not even mentioned in discussions of measurement.

It is conventional in physics to distinguish between two types of ratio scales: *fundamental* and *derived.* Fundamental scales are represented by length, weight, and electrical resistance, whereas derived scales are represented by density, force, and elasticity.

These latter are *derived* magnitudes in the sense that they are mathematical functions of certain fundamental magnitudes. They are actually more numerous in physics than are the fundamental magnitudes, which are commonly held to be basic because they satisfy the criterion of *additivity.* Weights, lengths, and resistances can be added in the physical sense, but this important empirical fact is generally accorded more prominence in the theory of measurement than it deserves. The so-called fundamental scales are important instances of ratio scales, but they are only instances. As a matter of fact, it can be demonstrated that the fundamental scales could be set up even if the physical operation of addition were ruled out as impossible of performance. Given three balances, for example, each having the proper construction, a set of standard weights could be manufactured without it ever being necessary to place two weights in the same scale pan at the same time. The procedure is too long to describe in these pages, but its feasibility is mentioned here simply to suggest that physical addition, even though it is sometimes possible, is not necessarily the basis of all measurement. Too much measuring goes on where resort can never be had to the process of laying things end-to-end or of piling them up in a heap.

Ratio scales of psychological magnitudes are rare but not entirely unknown. The Sone scale discussed by the British committee is an example founded on a deliberate attempt to have human observers judge the loudness ratios of pairs of tones. The judgment of equal intervals had long been established as a legitimate method, and with the work on sensory ratios, started independently in several laboratories, the final step was taken to assign numerals to sensations of loudness in such a way that relations among the sensations are reflected by the ordinary arithmetical relations in the numeral series. As in all measurement, there are limits imposed by error and variability, but within these limits the Sone scale ought properly to be classed as a ratio scale.

To the British committee, then, we may venture to suggest by way of conclusion that the most liberal and useful definition of measurement is, as one of its members advised, "the assignment of numerals to things so as to represent facts and conventions about them." The problem as to what is and is not measurement then reduces to the simple question: What are the rules, if any, under which numerals are assigned? If we can point to a consistent set of rules, we are obviously concerned with measurement of some sort, and we can then proceed to the more interesting question as to the kind of measurement it is. In most cases a formulation of the rules of assignment discloses directly the kind of measurement and hence the kind of scale involved. If there remains any ambiguity, we may seek the final and definitive answer in the mathematical group-structure of the scale form: In what ways can we transform its values and still have it serve all the functions previously fulfilled? We know that the values of all scales can be multiplied by a constant, which changes the size of the unit. If, in addition, a constant can be added (or a new zero point chosen), it is proof positive that we are not concerned with a ratio scale. Then, if the purpose of the scale is still served when its values are squared or cubed, it is not even an interval scale. And finally, if any two values may be interchanged at will, the ordinal scale is ruled out and the nominal scale is the sole remaining possibility.

This proposed solution to the semantic problem is not meant to imply that all scales belonging to the same mathematical group are equally precise or accurate or useful or "fundamental." Measurement is never better than the empirical operations by which it is carried out, and operations range from bad to good. Any particular scale, sensory or physical, may be objected to on the grounds of bias, low precision, restricted generality, and other factors, but the objector should remember that these are relative and practical matters and that no scale used by mortals is perfectly free of their taint.