The Lagoon How Aristotle invented science

Armand Marie Leroi (Penguin Books 2014)

7 But most of Aristotle's science isn't descriptive at all: it's answers to questions, hundreds of them. Why do fishes have gills and not lungs? Fins but not legs? Why do pigeons have a crop and elephants a trunk? Why do eagles lay so few eggs, fish so many, why are sparrows so salacious? What is it with bees, anyway? And the camel? Why do humans, uniquely, walk upright? How do we see-smell-hear-touch? What is the influence of the environment on growth? Why do children sometimes look like their parents, and sometimes not? What is the purpose of testicles, menstruation, vaginal fluids, orgasms? What is the cause of monstrous births? What is the real difference between male and female? How do living things stay alive? Why do they reproduce? Why do they die? This is not a tentative foray into a new field: it's a complete science.

His explanations penetrate his philosophy. There is a sense in which his philosophy is biology—in which he devised his ontology and epistemology just to explain how animals work. Ask Aristotle: what, fundamentally, exists? He would not say—as a modern biologist might —'go ask a physicist'; he'd point to a cuttlefish and say that.

13 D'Arcy Thompson translated *Historia Animalium* in 1910.

18 IT's NOT THAT there wasn't any science—or at least natural philosophy—before Aristotle... The Greeks called them physiologoi, literally 'those who give an account of nature'. Many were bold theoreticians.

A comparison of two near contemporaries illustrates the shift in thought. For the mythographer Hesiod (fi. 650 BC) earthquakes are the consequence of Zeus' wrath; for the first of the natural philosophers, Thales of Miletus (fi. 575 BC), they are the result of the earth's precarious location, adrift on an expanse of water occasionally roiled by waves. The difference could not be more clear-cut: on the one hand an explanation that invokes supernatural beings of fathomless antiquity; on the other an explanation that depends on purely physical forces—and never mind if it's wrong. Yet the comparison is not quite what it seems. For one, we can't be sure if that was really Thales.

20 Aristotle would call Empedocles' style 'lisping'.

It may seem that all Aristotle needed to do to become a scientist was to broker a marriage between the questing, querulous physiologoi and the dourly empirical medics. Which is what he did. That he managed it, however, is a tribute to the power of his mind.

22 By the time the teenaged Aristotle arrived at Athens to sit at Plato's feet, the tradition of natural philosophy, no more than two centuries old, was dead. Literally so: Democritus of Abdera, the last and greatest of the physiologoi, had died just a few years earlier. Years later, Aristotle would see in Democritus a formidable adversary, a foil against which to test the mettle of his own system. Democritus, Aristotle says, made advances. 'But [even] at this time men gave up inquiring into nature, and philosophers diverted their attention to political science and to practical goodness.' He was talking about Socrates.

Disillusioned by the physiologoi's singular lack of interest in discussing why the universe was good, Socrates turned away from the study of the natural world.

26 Then, too, if Plato's science is barely distinguishable from theology so, to judge by the pronouncements of some physicists, is modern science: 'If we discover a complete theory, it would be the ultimate triumph of human reason—for then we should know the mind of God.' Plato? No, Hawking. The comparison doesn't save Plato.

27 Aristotle would turn his back on his teacher's idealism and see the world, our world, for what it is: a thing that is beautiful and so worth studying in its own right. He would approach it with the humility and seriousness that it deserves. He would observe it with care and be unafraid to dirty his hands doing so. He would become the first true scientist. That he made of himself this after having been taught by one of the most persuasive intellects of all time—that is the mystery of Aristotle. All he ever said by way of explanation is: 'piety requires us to honour truth above our friends'.

38 Scientists, who are much less exercised about definitions, simply recognize their kin but, if pressed, might offer something like 'A scientist is someone who seeks, by systematic investigation, to understand experienced reality.' This definition, a generous one, allows room for theoretical physicists and coleopterists and some sociologists too; and, though we may quibble about the edges, it narrows the field of human activity considerably, excluding gardeners and physicians (no systematic investigation), literary critics and philosophers (no experienced reality), as well as homeopaths and creation—'scientists' who fail on both counts.

To be sure, Aristotle never called himself a 'scientist', but he did have a term for 'natural science'—physike episteme, literally the 'study of nature'.

39 Aristotle does not mean 'know' just in the sense of 'understand'; he also means 'perceive'. ... For Aristotle goes on to argue that 'knowing' in the sense of 'perceiving' is the foundation of 'knowing' in the sense of 'understanding'—indeed, is a requirement for wisdom.

40 Brute empiricism of that sort is useful, says Aristotle, but really not that admirable. In fact, he's very severe on mere empiricism and compares labourers undertaking tasks learnt by rote to 'lifeless things': they do what they do merely because that is what they do.* Masterworkmen who understand the whys of their craft are 'more honourable and know in a truer sense and are wiser' than such machine-men. (Politics 1253b31: 'A slave is a living tool ... ')

Aristotle is launching a new kind of philosophy: one that is neither concerned with the search for absolute values nor predicated on a perfect world beyond the senses.

40 ARISTOTLE's SCIENTIFIC METHOD is all of a piece with his epistemology. We have to begin, he says, with the phainomena —whence comes our 'phenomena', but perhaps the best translation is 'appearances', for he means by this not only what he sees with his own eyes, but also what other people have seen, and their opinions about it.

44 Aristotle himself doesn't scorn popular wisdom. He often says that we should begin investigations by considering what most people think, for they are often right.

51 But the most puzzling aspect of his exotic zoology is how he manages to combine exact knowledge with profound ignorance. ... The rest of Aristotle's exotic zoology is equally erratic.

55 But Callisthenes was no mere propagandist. He was also a natural philosopher capable of explaining the cause of the Nile's annual flood.... A fragment says that he sent information to Aristotle, though what about we do not know. Callisthenes followed Alexander's battle train for seven years. He was present at the sack of Tyre and of Gaza, the entry into Oasis Siwa, the battles of the Granicus, lssus and Gaugamela ... Aristotle never saw his nephew again. Somewhere in Bactria, modern-day Afghanistan, Alexander had the historian arrested and executed. .... Aristotle says nothing about his nephew's fate, but Theophrastus, the plant collector, mourned Callisthenes and wrote a dialogue in his name.

67 To determine the veracity of Aristotle's observations would take a squadron of zoologists, deeply versed in his thought and able to read ancient Greek, many years. Today such zoologists are rare. A few centuries ago, however, they weren't. Many could, and did, read Aristotle in the original. They loved what they found. Cuvier set the tone: 'In Aristotle everything amazes, everything is prodigious, everything is colossal. He lived but sixty-two years, and he was able to make thousands of observations of extreme delicacy, the accuracy of which the most rigorous criticism has never been able to impeach.'

74 Many zoologists have praised Aristotle, for they have seen him as one of their own. Some, in their enthusiasm, have ignored his defects; they have attributed to him their own insights and obsession with accuracy by way of compliment. However, one scholar and zoologist's assessment seems to me particularly beautiful and just:

> Now I take it that in regard to biology Aristotle did much the same thing as Boyle, breaking through a similar tradition; and herein one of the greatest of his great services is to be found. There was a wealth of natural history before his time; but it belonged to the farmer, the huntsman and the fisherman—with something over (doubtless) for the schoolboy, the idler and the poet. But Aristotle made it a science, and won a place for it in Philosophy.
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> Thus D'Arcy Thompson.

79 Aristotle's point is that spontaneous events are those that appear to have a purpose but in fact don't. And that is the nub of the matter: Aristotle thinks that the cosmos—the stars, the planets, the earth, the living things it contains, the elements themselves—obviously have a purpose; they show the hallmarks of design.

Only a child would ask 'what are the stars for?' But that's not a childish question to Aristotle.

81 Many early natural philosophers, Simplicius remarks, had this idea. That, if true, is remarkable, for it suggests that in Aristotle's time the idea of selection as a source of order was a commonplace. Certainly Epicurus, a generation younger than Aristotle, gave an even more elaborate selection-based cosmogeny than did Empedocles—at least he did if Lucretius' Epicurean verses are to be relied on.

82 The heart of Aristotle's rejection of materialism is his conviction that the cosmos, and the creatures it contains, have order and purpose. His dismissal of Democritus' conviction that order can simply arise spontaneously is, perhaps, understandable.

85 It's not that there aren't some interesting ideas in The Timaeus. Aristotle uses many of them in his zoology. But Plato, characteristically, does not think that we should accept his

divine teleology on its scientific merits. In Laws he explains that materialism - the materialism of Empedocles and Democritus—is malignant, for, dispensing with divine purpose, it leads to atheism and so social disorder. There's a moral sting in every Platonic tale.

86 Aristotle was deeply impressed by the resemblance between organisms and artefacts, particularly machines. ... Yet repeatedly and decisively he denies that there is a divine craftsman who made it all. There's no room for a Demiourgos in Aristotle's cosmos because it was not made; it's always been there. Besides, a craftsman isn't needed. Consider, he says, the apparently purposeful actions of animals: the way a spider weaves its web or a swallow makes its nest.

89 When using eidos in this sense Aristotle usually speaks of forms within a kind: 'There are many eide of fishes and birds.' Which brings us to the second sense of eidos—as the fundamental unit of biodiversity, that is, close to what we mean by 'species'.

It is the 'information' or the 'formula' which was transmitted to it by its parents, from which it built itself in the egg or womb, and which it will, in turn, transmit to its progeny. It is in this sense that Aristotle thinks that the nature of a thing resides primarily in its form. To speak of eidos as 'information' risks anachronism.

90 Aristotle's belief that we should attend less to the matter than to the informational structure of living things makes him seem like a molecular geneticist avant la lettre.

91 All these kinds of causes complement each other, indeed, are deeply intertwined. Or so Aristotle argues in a famous methodological dictum known as the 'four causes'. But 'cause' isn't quite right: 'four questions' or 'four kinds of causal explanation' capture his meaning better:

There are four basic causal explanations: first, what something is for (i.e. what its goal is); second, the formal cause or 'definition of the essence' (these first two should be treated as pretty well the same thing); third, its material basis and, fourth, its efficient cause or origin of movement.

I take them in reverse order. The efficient (or moving) cause is an account of the mechanics of movement and change. It is now the domain of developmental biology and neurophysiology. The material cause is an account of the matter—the stuff—of which animals are made, and their properties. It is now the domain of modern biochemistry and physiology. The formal cause is an account of the information transmitted that any creature received from its parents, and that is responsible for the features that it shares with other members of its species—that is, the subject matter of genetics.

Four causes are research programs.

98 THE NATURAL PHILOSOPHERS of the Renaissance looked at the world with curiosity, discovered that they knew almost nothing about it and turned, quite naturally, to Aristotle as one who did. For them Aristotle was primarily a naturalist who sought to give a comprehensive account of all the creatures that he knew,.

103 Aristotle also recognized larger groups as Genera, Families, Orders, Classes and Phyla. He
105 calls them *megista gene*—greatest kinds .... He recognized a nested hierarchy.

116 Contra Cuvier, Aristotle never produces anything resembling a coherent comprehensive classification in which every animal has its place.

118 Even so, modern scholars generally agree that it does have a clear purpose. Beneath the disorder, it provides the materials for a data trawl. Aristotle is searching for patterns—patterns of a very subtle sort. He isn't interested merely in how parts vary, but also in how they covary.

123 Aristotle distinguishes the rules for debating opinions from the rules for constructing scientific explanations. The first he called 'dialectic', the latter 'demonstration' (the Greek is apodeixis).

125 Aristotle, however, would point to the middle term of the syllogism—the Pitx1 mutation—as the causal link and give a definition of the following sort: 'a lake stickleback is one that lacks pelvic spines because it has a Pitx1 mutation'. That's demonstration, he would say; that's science. Such definitions are the logos—the 'essence' or 'formula' of the things he studied. So his scientific method turns out to be a way of expressing the fundamental causal identities of things shorn of all incidental, and hence scientifically uninteresting, features.

127 Some people, he says, claim that scientific knowledge is impossible because any inference we make must rely on some previous inference, and that must rely on another, and so on to infinity so that, ultimately, we can know nothing. Other people, he continues, claim that anything can be demonstrated: everything is true hence nothing is true. Aristotle recognizes that both thoughts are lethal to the possibility of science, and he deals with them briskly. No, there isn't an infinite regress of inferences, nor is it true that everything can be demonstrated, because our arguments ultimately begin with axioms and our perception of the empirical world.

149 He also supposes that more complex animals tend to have more specialized parts.

These auxiliary principles pervade his explanations of diversity. Nature's good housekeeping explains (or helps explain) the presence and absence of all sorts of weakly functional organs such as eyebrows, spleens and kidneys. That nature does nothing in vain explains inter alia why fish don't have eyelids, lungs or legs, why fanged animals don't have tusks, why only animals with molars grind their teeth from side to side, why our teeth last as long as they do and why males exist. The fact that nature can only give to one part what it's taken from another explains inter alia why sharks don't have bones, why bears don't have hairy tails, why birds don't have bladders, why lions have only two teats, why birds have either talons or spurs but not both and why the frogfish has its funny shape. It also explains much of life-history variation and why we die.

Collectively these auxiliary principles are a model of the body's economic design.

157 Aristotle asserts, with fairly little argument, two propositions: that all living things—plants, animals and humans—have souls; and that, when a living thing dies, its soul ceases to exist. These were probably commonplace among fourth-century Greek intellectuals.

I have argued that, when Aristotle speaks of the 'form' or 'formal nature' of a creature, he often means the information required to order matter into a creature of a given kind. This interpretation is based not only on the various analogies he gives (imprints in wax; letters and syllables), but also on the fact that forms are present even when they are invisible. They are somehow present in an animal's seed and are responsible for the development of the embryo and the appearance and functions of the adult. So an animal's soul

is its form, albeit under particular circumstances:

If we must say something general about all types of soul, it would be the first actuality of a natural body with organs.

The key word here is 'actuality'—entelekheia. It is this word, a bit of Aristotelian jargon, that is most distinctive about his theory of the soul.

[**C**] Soul $\rightarrow$ form $\sim$ information?

159 actuality, he's stressing the fact that it's something that previously existed only potentially; that it's something that comes into being from something else. When combined with the claim that the soul of a living thing is 'its form in its body', it becomes clear that he means that the forms of unfertilized seed are mere potentials; and that those forms when realized in growing embryos and functioning adults are souls.

The soul, he says, is 'an entity [ousia] in the sense of a definition [logos]'. By this he means that a living thing's soul is the sum of its functional features. If an eye were a living creature, he says, then its soul would be vision. He is so committed to the idea that.functional features define a creature (or an organ), rather than the stuff it's made of...

160 SOULS, THEN, BEAR a heavy burden. They embrace no fewer than three of Aristotle's four explanatory causes - the formal, moving and final—leaving only the material cause for the stuff of which it is made.

163 The belief that living things transform food into uniform parts hardly seems like a stunning insight, yet it seems to have been original to him.

165 The structure of the metabolic network—is the nutritive soul.

167 We must imagine Aristotle sitting in front of a hearth (as Heraclitus was said to do), staring into the fire, occasionally poking it, thinking about the fire that rages inside him, that keeps him alive, that permits his thoughts to flow apparently without cease, devouring the world. 'Fire is always coming into being and flowing like a river'—how very true. But no fire can rage unchecked for ever lest it consume itself. All fires must be fuelled, stoked, damped—regulated—if the tenuous flame of existence is to be maintained. That, too, is the work of the soul.

Where is the soul located? The Aristotelian answer is 'everywhere' and 'nowhere'.

171 The term that Aristotle uses for the mental representation of some object is *phantasia*.

178 Of course, the point is not to make Aristotle seem terribly modern. Rather, it is to better understand his answers to some of biology's deepest questions. What gives living things their goal-directedness? Souls do - by which he meant control systems of a complexity sufficient to show goal-directed behaviour. What holds living things together? Souls do—by which he meant the functional interconnections of their parts. How should we study living things? We have to take them apart, reduce them down to their individual bits and pieces. But, having done so, we also have to put them back together again for it is only then that we really understand how they work.

191 It is insightful for it captures the idea that the seed contains something—the form—that

is not the animal itself but that has, nevertheless, the power both to shape and to become it, and that ontogeny is the process by which this potential is translated into an actual living, breathing, copulating creature.

Yet Aristotle's aim is clear: he's trying to show that the power of semen to direct development rests not on the transmission of seminal matter itself, but on something else.

What? Something in semen must get to the embryo, and if it isn't seminal matter then what is it? To solve this problem Aristotle once again invokes that mysterious stuff, pneuma. It's not only an instrument of the sensitive soul, but also a component of the inheritance system. .... The upshot is a theory for how an animal's soul is reproduced in the embryo. The structure of the father's soul is, in effect, encoded in his semen by pneumatic action.* We must not think of pneuma as the carrier of genetic information itself: it's not Aristotelian DNA. Rather, Aristotle's units of inheritance are much more abstract; they're the movements that pneuma induces in the semen.

211 Here, at least, Theophrastus is closer to the phenomena than Aristotle. We sense that the student was a gardener, but that his teacher just peered over the farmyard fence. But the two scientists complement each other. Theophrastus' theories are thin. How is variation inherited? He doesn't really say. Aristotle does.

233 And so puzzle remains. Aristotle believes in spontaneous generation even though the animals that he knows best all have parents. He believes it even when his own data on particular animals—those pesky flies - point the other way. He believes it even though to make it work he has to distort his own—brilliant—theory of development. He believes it even though it contradicts his metaphysics and gives the game, the hard-fought game, to his materialist opponents. He believes it even though there's a simple alternative explanation ready to hand. So why does he believe it?

264 Adaptive = teleological

272 Indeed, reading Aristotle, it's easy to suppose that he is struggling towards, or even has, a theory of evolution. He isn't and hasn't. Nowhere in his works does he claim, as Darwin did, that all animals are descended from some remote common ancestor. Nowhere does he suggest that one kind of animal can transform into another. Nowhere does he lament some kind that has gone extinct. Genos, he says, is a word that can be used in several different senses—but there's no hint that, in the biology, he's using the genealogical one.

275 In fact it is certain that Darwin knew little about Aristotle that wasn't fragmentary or second-hand before 1882 which is when William Ogle, physician and classicist, sent him a copy of The Parts of Animals that he had just translated along with the following letter:...

It was just the book to send to Darwin. A few weeks later, Darwin replied to Ogle thanking him for the book:

From quotations which I had seen I had a high notion of Aristotle's merits, but I had not the most remote notion what a wonderful man he was. Linnaeus and Cuvier have been my two gods, though in very different ways, but they were mere school-boys to old Aristotle.

When Darwin said that his 'two gods'—Linnaeus and Cuvier—were mere schoolboys compared to Aristotle, he was insufficiently precise. He should have said that old Aristotle taught them.

ARISTOTLE's CLASSIFICATION OF the animals is the starting point of our own. Linnaeus got many of his European species from him, either directly or via the sixteenth century encyclopaedists. .... Aristotle's higher taxa—the megista gene—are also the basis of ours..... Aristotle's influence on Linnaeus is not only apparent in his actual taxa. At least some of his taxonomic terminology, most obviously species (eidos) and genus are ultimately Aristotelian or Platonic.

285 Perhaps Aristotle's most important legacy is one that I have not touched on at all, but that also runs throughout the history of zoology. It is his insistence that the organic world is structured into natural classes that our classifications should not tear apart.

289 Our conceptual world is structured on a Manichean conflict between creationism and evolution. The conceptual world of the Greeks, before and after Aristotle, was structured on a conflict between creationist and naturalistic explanations for the origin of its living inhabitants. For Aristotle, there's not much to choose between them. Both fail to grasp one of the most salient features of the biological world: its regularity.

For Aristotle, the origin of any individual of a given sexual kind requires the existence of two others of the same kind. To make a sparrow you first need two other sparrows. His slogan, 'a human being gives rise to a human being', applies, mutatis mutandis, to all sexual kinds. Only parents—more precisely, the father—can supply the form, the eidos, required to make a new individual. This theory, taken literally, implies arr eternal regress of sparrows. Aristotle takes it literally.

298 WILLIAM OGLE, WHO loved Darwin and Aristotle both, wished they could have met in person. In his letter to Darwin he imagines the Greek arriving at Down House. Aristotle considers Darwin with suspicion. He scans, as authors do, the study's bookshelves for his own works. He is astonished, as authors are, to find them not there - as, indeed, they weren't....

Aristotle understands as Darwin did and we do that: (i) the complex morphologies and functions shown by living things require a primal source of order or information, his 'formal natures' or simply 'forms'; (ii) that these forms are dynamic, self-replicating systems; (iii) that they vary among kinds to give diversity; (iv) that they exert their power by modifying the flow of materials in development and physiology; (v) that organisms gain these materials from nutrition which is transformed internally; (vi) that this material is limited in quantity; (vii) that the manufacture of parts, production of progeny, indeed survival itself, all expend this material—that is, are costly; (viii) that these costs limit the forms and functions of organisms such that if they do or make one thing it is at the expense of not being able to do or make another; (ix) that these costs are not absolute: some organisms are more subject to them than others; (x) that these material constraints act in concert with functional demands to give the diversity of animals that we see in the world; (xi) that the parts of animals are suited to the environments in which they live, that they are, in a word, adaptations; (xii) that the functions of different organs depend on each other - that is, living things must be understood as integrated wholes. Much of modern evolutionary science is in this list—but evolution isn't.

The history of Western thought is littered with teleologists. From fourth-century Attica to twenty-first century Kansas, the Argument from Design has never lost its appeal. Aristotle and Darwin, however, share the more unusual conviction that though the organic world is filled with design there is no designer. But if the designer is dead for whose benefit

is the design? It's the prosecutor's question: cui bono?

Darwin answered that individuals benefit. Biologists have batted the question about ever since. The answers that they've essayed are: memes, genes, individuals, groups, species, some combination or all of the above. Aristotle, however, generally appears to agree with Darwin: organs exist for the sake of the survival and reproduction of individual animals. This is why so much of his biology seems so familiar.

Yet there is a deep difference between Aristotle's teleology and Darwin's adaptationism, one that appears

311 Aristotle's political science is very sociobiological.

353 Medawar wrote these lines in 1985.* Their tone, however, is pure seventeenth century. It's the tone of the early Royal Society of London, the association of scientists of which Medawar was rightly proud to be a Fellow. The anachronism explains all. Medawar's abuse was aimed not at Aristotle the father of science but at Aristotle its greatest foe. He was, indeed, re-enacting, for a new generation, the origin myth of modern science; the myth in which Aristotle was the giant who had to be slain so that we could pass through the straits of philosophy to reach the open sea of scientific truth. that lay beyond; the myth in which Aristotle is little more than an endlessly fecund source of empirical, theoretical and methodological error;

Aristotle's science was the principle casualty of the Scientific Revolution. It may even be said that modern science was built on its ruins.

353 The triumph of the Thomist synthesis rendered Aristotle's philosophy supreme. In Inferno IV, published around 1317, Dante called Aristotle 'the master of those who know'. The cost of philosophy was science. Following Thomas, the schoolmen of Oxford, Coimbra, Padua and Paris toyed endlessly with substance, potentialities, form-and-matter compounds, categories and all the other cogs in the Philosopher's metaphysical machine. Their method was disputatious, their factions innumerable, their writings interminable and their conclusions stultifying. Much of it wasn't very Aristotelian at all. They reigned over Europe's universities for three centuries.

355 ARISTOTLE's PHYSICAL SYSTEM suffered grievously at the hands of the new scientists. By the middle of the seventeenth century his cosmology and theory of motion were obsolete. His chemistry took longer to kill. His biology, rich in empirical data, fared best. Even in the thirteenth century Albert Magnus drew from it the right conclusions. 'The aim of natural science', he wrote, 'is not simply to accept the statements of others, but to investigate the causes that are at work in nature.' And: 'Experiment is the only safe guide in such investigations.' He accordingly added much new animal lore, some of it first hand, some borrowed from other sources, to his synopsis of Aristotle's zoology. Compare Albert's use of Aristotle to Thomas's and it is hard to resist the conclusion that the eclipse of the former by the latter retarded the development of natural science by centuries.

This thought gains additional force from the fact that in the sixteenth century Aristotle's biology helped to break the hold of Thomist scholasticism. In 1516 Pietro Pomponazzi, professor at Bologna, published Tractatus de immortalitate animae, in which he counterposed the Thomist doctrine of the immortality of the soul, established as dogma by the Fifth Lateran Council of 1512, against Aristotle's argument for its mortality.

356 Yet it was neither his association with scholasticism nor his zoological errors, nor even the falsification of his physical theories, that accounts for the oblivion of Aristotle's scientific

thought; for the fact that, if he is remembered as a scientist at all, it is as a muddleheaded ancient (scarcely distinguishable from Pliny), rather than as the engineer of the greatest scientific structure ever built by one man, and the first to boot; rather, it was the belief, a foundation stone of the New Philosophy, that his explanatory system was corrupt to its core. And here Medawar gets it right. For he credits—no, celebrates—one man for having done more than any other towards the destruction of Aristotle's reputation. Enter Francis Bacon.

359 Bacon's most serious charge was aimed at Aristotle's explanatory system. Of the four kinds of causal explanations that Aristotle insists natural science demands, Bacon ruled two—the formal and final - illegitimate. Natural philosophy should concern itself with the properties and movements of matter and them alone.

Bacon's aversion to Aristotle and Aristotelianism— he scarcely distinguishes the two—also stemmed from a particular vision of the purpose of science and its proper object of study. Its purpose, in Bacon's view, was not merely to understand the world, but to change it; its proper object of study, then, was the artificial rather than natural. Bacon was a technology enthusiast.

In biology, the cheerleader of mechanism was Descartes. Animals and plants, he declared, do not have souls—they are merely machines. This was the doctrine of the bete machine or beast machine. Descartes reduced the complex of Aristotelian changes to local motion alone, and founded his physiology on a corpuscularianism that he got from Gassendi and Beeckman.

361 BACON AND HIS successors said that Aristotle's methods were wrong and that his explanations were too. Both charges are grave, but are they just? Our ideas of what constitutes scientific explanation, and how to achieve it, are ever changing. It may be, then, that we can see merits in Aristotle that our predecessors missed. Every generation must read Aristotle anew.* That Aristotle made countless observations of the natural world is obvious to anyone who reads his books—even the men of the Royal Society conceded so much. Should you read Aristotle's biology, you may, however, wonder why Bacon and Glanvill...

368 THERE 1S A belief, and I think it is a very widespread one, that something is wrong with Aristotle's explanations; that they are, in some way, fundamentally unscientific. Sometimes it is said that his appeal to the 'natures' of things is circular. In Le Malade imaginaire, 1673, Moliere's Aristotelian quacks explain that opium induces sleep because it possesses a sleep-inducing principle. Ever since, arguments of this kind have been known as virtus dormitiva explanations and rightly treated with scorn. At other times it is said that Aristotelian natures possess a 'creative impulse' or else 'occult forces'. Applied to his biology, these are polite ways of saying that he's a vitalist—which many have said too. And then there are those who have said that final or formal causes are those creative impulses and occult forces and have no place in modern science. All of these charges, endlessly repeated, are echoes of the Scientific Revolution. Often they have been repeated by Aristotle's foes who knew little of what he said or did. Yet even those who have known Aristotle intimately, and loved him dearly, have sometimes...

370 In this book I have sketched Aristotle's account of five interlocked biological processes: (i) the nutritional system by which an animal takes up complex matter from its environment, alters its qualities and redistributes it to its various tissues so that it can grow, thrive and reproduce; (ii) the thermoregulatory cycle by which it maintains itself and which, as it ages, falls

apart; (iii) the CIOM system by which an animal perceives and responds to its environment; (iv) the epigenetic processes of embryonic development and its related spontaneous-generator version; (v) the inheritance system. All of these processes are underpinned by Aristotle's physical theory and are, as such, mechanistic. That the physical theory is wrong is irrelevant; in the long run, all physical theories are.

All these processes explain some part of the workings of the soul. But soul is not something superadded to them: they are, collectively, soul; more precisely, soul is the dynamic structure of these physical processes (or their result). Again, that Aristotelian souls run on an obsolete theory of motion, a defunct chemistry and an oft-erroneous anatomy is beside the point. Descartes, for all his bete machine rhetoric, had his animals move by means of 'animal spirits' percolating through their nervous systems—pneuma by another name. If Aristotle's biology becomes unmechanistic at any point, it's when he considers higher cognitive functions—phantasia, reasoning, desire. They're merely black boxes. But we can forgive him this—they are for us too.

Although mechanical similes are not needed for a theory to be mechanistic, they are often the sign of one. When explaining how animals work Aristotle incessantly invokes them. Bellows, irrigation ditches, porous pottery, cheese-making, toy carts and, of course, those enigmatic automatic puppets, all appear in his biology. For all that, he never draws the Cartesian comparison of a whole creature to a machine. Doubtless this is because the mechanical devices of Aristotle's day were so rudimentary.* We can see that his heart-lung cycle is a thermostat but he obviously didn't—he just said how he thought it all works.

This, then, is Aristotle's dilemma. He sees that artefacts and living things are both made of more basic stuff, that they change and that these changes must be explicable in terms of physical principles. Yet, when looking at his world, he also sees that there is no artefact remotely capable of doing what creatures so effortlessly do. His solution is to acknowledge the parallels but keep them firmly apart. The cybernetic properties of living things even cause him to give them the special ontological status of 'entities' —ousai—while denying that status to artefacts. He would surely have dismissed Descartes' talk of beast machines as empty rhetoric. In Descartes' hands it was. It wouldn't stay that way.

Aristotle's enemies (and some of his friends) have also made formal and final causes far more mysterious than they really are. Aristotle saw that complex objects —and nothing is more complex than a living thing cannot assemble willy-nilly by chance but must be modelled on a pattern located elsewhere. Long absent from science, molecular biology made
373 form—eidos—respectable again. In What is Life? Schrodinger, quoting Goethe ('Being is eternal; for there are laws to conserve the treasures of life on which the Universe draws for beauty'), argued that the chromosomes, which he envisioned as aperiodic crystals, contain a 'code-script' and are 'the law-code and executive power—or, to use another simile, they are architect's plan and builder's craft—in one'. The last is one of Aristotle's similes too. It was Max Delbrück at Caltech who made the connection explicit. In his charming essay 'Aristotle-totle-totle'[1] he told of how, in the course of a long correspondence with Andre Lwoff at the Institut Pasteur in Paris, he discovered the Philosopher's works. After quoting bits from The Generation of Animals he wrote, 'What all of these quotations say is this: The form principle is the information which is stored in the semen. After fertilization it is read out in a preprogrammed way; the readout alters the matter upon which it acts, but it does not alter the stored information, which is not, properly speaking, part of the finished product.' And then he suggested that, were Nobels handed out posthumously, Aristotle should get one for discovering the principle (if hardly the substance, much less the structure) of

[1] "I should like to utilize this opportunity to state the conjecture that this wonderful man discovered DNA. Let me explain" (in "Of Microbes and Life" J Monod and E. Borek, eds. Columbia UP 1971).

DNA. In 1969 Delbrück got one for his work on mutation.

Final causes, too, have been demystified. Aristotle saw that they are needed when the phenomenon to be explained appears to have a goal. They arise then as the answers to several related questions which he asked and which modern biologists do too. When we ask why do goal-directed entities exist, we give Darwin's answer: because evolution by natural selection produced them. That is shorthand for the whole edifice of population genetic theory that renders benevolent creators null and void. When we ask what their goals are, we answer by pointing to all the adaptive devices that allow them to feed, move, mate, defy their predators and, ultimately, survive and reproduce. It is Bacon's sneers at teleological explanations of this sort, those 'remoras and hindrances', that now look quaint. To argue, as he did, that the functional study of eyelashes, skin and bones should be no part of science is to betray a remarkable incuriosity about the point of one's own body.

We can also ask how goal-directed things, living or not, work. That is the most difficult kind of final explanation, and its answer lies in the beating heart of the science of complex objects. Cybernetics, General Systems Theory and Control Theory formalize the general principles; systems biology shows those principles at work in living things; synthetic biology how those same principles can be used to reshape them. In 2010 JCVl-syn1.0,[2] the world's first artificial cellular life form, fired its molecular motors. The distinction between artefact and organism dissolved in a Petri dish.

Aristotle's answers to these questions, all of which are embraced by his final cause, are sometimes similar to ours and sometimes, but hardly surprisingly so, very different.

rmp373Aristotle could not have conceived just how vast the science that he founded would become. Yet, as I contemplate the elaborate tapestry of his science, and compare it to ours, I conclude that we can now see his intentions and accomplishments more clearly than any previous age has seen them and that, if this is so, it is because we have caught up with him.

375 Aristotle, I believe, would have too. Intimacy with the natural world shines from his works; it does from Theophrastus' as well. This intimacy allowed them, the men of the Lyceum, to begin the process of sieving the ocean of natural history folklore and travelogue for grains of truth from which to build a new science.

Aristotle even said so: Failure to understand what is obvious can be caused by inexperience: those who have spent more time with the natural world are better at suggesting theories of wide explanatory scope. Those who have spent time arguing instead of studying things as they are show all too clearly that they are incapable of seeing much at all.

377 As we age we become trapped by our habits of mind, by what we already know, as surely as fish are in the sea. Science, the glittering medium in which we swim, dictates what we see. That is how it should be and inescapably is, for no one sees the world unmediated by theory and expectation. Yet how we long to see it afresh. 'For as the eyes of bats are to the blaze of day, so is the reason in our soul [oblivious] to the things that are most evident of all'—Metaphysics 993b10. Aristotle, armed with the method that he discovered, that precarious combination of theory tempered by experience that is the essence of science, turned to a part of the world that no one had ever looked at before, described it, explained it and, as Thompson said, won for it a place in Philosophy. We can envy him for have doing so. Swept along in the seething currents of scientific progress we struggle to emulate him. But

[2] **[C]** This is a Venter business, so "The distinction between artefact and organism dissolved" is still false.

Aristotle shows us what we must do.

378 Aristotle wrote thousands of sentences, but one, the first of his Metaphysics, defines him: 'All men, by nature, desire to know.' Not all forms of knowledge, however, are equal—the best is the pure and disinterested search for the causes of the things. And, he has no doubt, searching for them is the best way to spend a life. It is a claim for the beauty and worth of science.