Chapter Two

A Critique of Plato's Biological Analogy

All true Christians are of one body in Christ.... All the parts of this body being thus united are made so contiguous in a special relation as they must needs partake of each others strength and infirmity, joy, and sorrow, weal and woe.... This sensibleness and sympathy of each others conditions will necessarily infuse into each part a native desire and endeavor, to strengthen, defend, preserve, and comfort the other.... The end is to improve our lives to do more service to the Lord the comfort and increase of the body of Christ whereof we are members that our selves and posterity may be the better preserved from the common corruptions of this evil world .... for this end, we must be knit together in this work as one man ....

John Winthrop, first governor of the Massachusetts Bay Colony
(from a sermon aboard the Arabella in 1630)

There are a number of other fundamental conceptual weaknesses in Plato's monistic model of the state. In this chapter I will examine one such weakness. Plato's insistence on the unity of the good leads inexorably to his theory of the polis as an organic whole. For Plato the health of the body is the result of the near perfect cooperation between its parts functioning for the good of the unit whole. Analogously, Plato's Kallipolis is conceived as a state in which everyone functions, in near perfect cooperation, for the good of the unit whole. It is fundamental to the argument of *The Republic* that the health of the state is analogous to the health of the body, and that, therefore, we can learn how to structure a healthy state by examining how health is achieved in the body. This view of biological health is central to Plato's vision of the just polis. Nevertheless, I will argue that this conception of biological health is based on an incorrect understanding of biological regulation. When we carefully examine biological regulation, we will see that Plato's monism will not tend to lead to healthy well-regulated cities but to dangerously unstable political cities.

Plato was neither the first nor the last political theorist to invoke the biological analogy. One hundred and fifty years earlier the physician Alcmaeon had advanced the analogy in support of a quite different vision of society. And after Plato, Aristotle, Hobbes, Rousseau, and Hegel, to name only a few, have each, in their own very different ways, invoked the image of the state as the body writ large. Most political theorists have perceived some similarities between the organization of the body and the organization of the state, the regulation of the body and the regulation of body politic. There has been considerably less agreement, however, on what those similarities are, and where the analogy should lead us.

Contrary to what Karl Popper claims in *The Open Society and its Enemies* there is little evidence that Plato himself believed that the state exists as a single organism, with a life, a history, and an historical destiny of its own. Unlike Hegel[1] Plato does not seem to have been concerned with either history or historians, much less historicism. He did not hold an organic view of the state in this sense. Nevertheless, the degree of unity required in Plato's Kallipolis effectively precludes the possibility of individual choices which may conflict with the interests of the whole as defined by the monistic vision of the good. This tendency to dissolve the individual into the state is a fatal flaw in any monistic view of the state. Plato, like Rousseau, saw the unity and harmony of the whole as the *only* legitimate way in which the interests and the rights of the individual citizen could be addressed. He recognizes no possibility of legitimate individual interests which do not in fact coincide with the needs of the state. It is doubtful that the notion of individual rights, as we understand it, existed in the ancient world. Plato speaks of individual interests and desires and not of rights. The notion of the rights of the individual become a major focus of political theory only with the Enlightenment. But even Rousseau, who does recognize the concept of individual rights, does not seem to allow for the legitimacy of individual rights or interests which happen to conflict with the General Will. Judging by Plato and Rousseau, Popper is correct in claiming that any appeal to the biological analogy which fails to recognize the interests and the rights of the individual is problematic. And Popper is correct when he argues that most appeals to the biological analogy do fail to adequately recognize the rights of the individual. As has often been argued with great eloquence and at considerable cost in human lives, a human being is something more than simply a component of the state.[2]

Although I am in complete agreement with these criticisms of the biological analogy, in this chapter I will argue that Plato's use of the analogy is fundamentally flawed in at least one other way as well. I believe that Plato's use of the analogy is flawed because he did not understand the nature of biological regulation. Therefore, even were we to see the state as a body writ large, we would not be led to Plato's political philosophy. It is as if Plato were saying that the ideal city plan is a square grid because the plan of the city should mirror the plan of the solar system and the orbit of a planet is a square. One could legitimately question what, if anything, the plan of the city has to do with the orbit of the planets, which is what Popper and others do when they attack the legitimacy of any analogy between the body and the state. But one could, as well, point out that the planetary orbits do not describe squares, and if they were to do so, such orbits would be in contradiction not only with the history of our observations of the heavens, but also with our understanding of the most fundamental rules of mechanics.

My claim then is that the biological analogy, as Plato conceives it, fails because Plato does not understand the nature of biological regulation.

It is the *wrong* biological analogy.

It would follow that to whatever extent the health of the state is analogous to health of the body, Plato's model of the healthy society could not be inferred from that analogy. When we examine the mechanisms by which biological regulation is accomplished we will be led to an entirely different set of conclusions about the political good. The model suggested by a correctly framed biological analogy will have more in common with the invisible hand mechanisms of Adam Smith than with the rational rule of Plato's Philosopher King, Rousseau's General Will, or Marx's classless society.

Stasis

In *The Republic* Plato argues that, just as the health of the body is dependent on the unity and near perfect cooperation of its functioning parts under the guidance and control of the intelligent part of the soul, so too, the health of the state is dependent on the perfect cooperation of the social orders under the intelligent guidance of men and women of knowledge. And in the same way that perfect harmony among the parts is essential to the health of the soul or the body, so too perfect harmony among the parts is essential to the health of society. *Stasis*, a word which is generally translated in *The Republic* as "divisiveness," "disunity," or "civil strife" is, for Plato, the ultimate evil in the state, the soul, or the body. Nevertheless, it is worth noting that not all Greek authors use the word *stasis* exclusively in this pejorative sense. The word "*stasis*" seems to have two meanings which are, to the Greek mind, related. It may mean "a posture," or "a standing," or "a class." In Latin this sense of *stasis* becomes "status." Therefore, *stasis*, as an adjective, may even be translated as "stable," "steadfast," "steady," "firm" or even "stagnant." In the alternative it may mean, "factious," "seditious,"" divisive," "discordant."[3] It is this second sense of *stasis* that is central to the thinking in *The Republic*. In *The Republic*, Plato uses *stasis* only in this negative sense.[4]

If justice is harmony and unity for Plato then injustice is civil strife (*stasis)*, the most dreaded of all evils.[5] What, Plato asks, is the ultimate evil in the soul? And he answers:

> It must certainly be a kind of civil strife (*stasis*) among the three parts when one part rebels and takes over another part's function, a rebellion of a part against the whole soul in order to rule it. And this is not right, as the rebelling part is not fitted by nature to rule but is fit only to be the servant of the ruling kind. We will say that such things, such turmoil, and aberration, are injustice, and license, and, cowardice, and ignorance, and, in a word, every kind of wickedness." (*Republic* 444b)

Justice in the state is unity, and unity is a lack of *stasis*. This is a recurring claim throughout *The Republic* particularly in Book IV where justice is first defined, and in Book VIII where Plato discusses how discord in the ruling group brings about the disintegration of cities.

Since, for Plato, disunity (*stasis)* is the greatest evil in the state, he is willing, as we have seen, to go to great lengths to eliminate possible causes of dissension. In his mind, such causes include private property, private family relations, and even poetic references to dissension among men and gods. Nor does Plato entertain any other notion of how the unity of the state might be accomplished except through the elimination of faction. Plato thus conceives of unity in a fairly straightforward way as a lack of disunity (*stasis)* and as Nicholas White claims, "He seems unconcerned with the possibility that the notion of unity might be construed in other ways.'[6]

This association of biological unity and regulation with a lack of *stasis* is shared by most of the political theorists who defend the biological analogy, as well as by many of the political theorists who attack it. Thus, for example, John Winthrop, founder of the Massachusetts Bay Colony, says of his "City on the Hill" that "we must be knit together in this work as one man ... our community as members of the same body.'[7] Rousseau's General Will is just such a unity, as is Marx's classless and therefore factionless[8] society. And even some of the opponents the organic society conceive of organic unity in this way. Karl Popper, that champion of the open society construes organic unity as a lack of *stasis*. According to Popper the closed society is analogous to an organic or biological body. It is, he claims "Impossible to apply the organic theory successfully to an open society,'[9] because in an open society there must be competition and, claims Popper, such competition is incompatible with the organic theory of the state. It seems clear that the elimination of *stasis* is often thought to be fundamental -- by friend and foe alike -- to any vision of society that relies on an organic model.

Even prior to Plato, however, other models for the unity of the body had been suggested. And they were models which embraced *stasis*. For the physician Alcmaeon (about 500 BCE) health was a matter of equality of rights (*isonomia*) which was to be achieved by a balance of opposites. Disease, on this account, then becomes *monarchia* or the rule of one.

> Health is the equality of rights of the functions, wet-dry, cold-hot, bitter-sweet and the rest; but single rule among them causes disease; the single rule of either pair is deleterious. Disease occurs sometimes from an internal cause such as excess of heat or cold, sometimes from an external cause such as excess or deficiency of food, sometimes in a certain part, such as blood, marrow or brain; but these parts also are sometimes affected by external causes, such as certain waters or a particular site or fatigue or constraint or similar reasons. But health is the harmonious mixture of the qualities.[10]

While Alcmaeon also speaks of harmony he means to achieve harmony by means of *isonomia* or equal rights -- by means of *stasis*. Since *isonomia* was a politically-laden term associated with Athenian democracy just as, *eunomia*, or good law, was associated with the Spartan Constitution,[11] we see that harmony for Alcmaeon, in both the body and the state, is not to be achieved by the simple elimination of all causes of dissension, but by maintaining a certain kind of balance. Reason, efficiency, and order are the trademarks of Plato's organic theory, while Alcmaeon saw biological regulation in terms of balancing naturally opposing elements.

Similarly, for Heraclitus, balance is achieved "By a thing being at variance with itself, it coheres with itself; a back-stretched harmony, as of a bow or a lyre...(DK B 51) One must realize that conflict (*polemos*) is innate to all things, and justice (*dike*) is strife (*eris*), and all thing come to pass according to strife and necessity (*chreon*)." (DK B 80) Heraclitus sees justice (*dike*) and harmony coming to be as a result of a process of conflict.

We do not know that Heraclitus' fragments refer to either biological or political regulation, but Alcmaeon's fragment directly addresses the nature of biological balance in terms which are quite clearly political. And Alcmaeon saw *stasis* as necessary to the regulation of the body and the state, and not as inimical to it. Developments in the science of physiology in the 19th and 20th centuries suggest that Alcmaeon's ideas about biological regulation were more accurate than Plato's.

Plato's Psychological Analogy

For Plato the health of the state is to be achieved not simply by unified control, but by means of unified rational or intelligent control. And so, Plato's arguments on harmony or regulation are often coupled with his discussions of rational control and, in this too, he establishes an analogy between harmony in the soul and harmony in the state. Although often overlooked there is a distinction between what might be called Plato's biological analogy and Plato's psychological analogy. Control of the healthy soul is consciously rational; control of the body may not be.

Plato developed his theory of the soul in a number of dialogues including *The Republic*, *The Phaedo*, and *The Phaedrus*. Plato is, of course, not a Christian and so his use of the term "soul" does not carry the religious meanings associated with Christianity or even Judaism. One might better think of Plato's soul as the psyche although, in its way that term is now also misleading since it seems to carry the meanings bestowed on it by the modern theories of psychology. Perhaps it is for that reason, that commentators, myself included, generally continue to use the word "soul" in discussing Plato. In any case, for Plato, the soul is tripartite. It consists of an appetitive part, a spirited part, and a rational part. For Plato, the harmony that is justice is achieved when the rational part rules the appetites. The appetitive part of the soul is the source, according to Plato, of conflict.

> We may call that part of the soul whereby it reckons and reasons, the rational part of the soul; and that part of the soul with which it lusts, experiences hunger and thirst, and feels the flutter and titillation of other desires, we will call the irrational appetitive part of the soul. It is the companion of pleasure and the replenishment of wants. (*Republic* 439d)

For Plato, generally speaking, the causes of disharmony (*stasis*) in the soul are ignorance and the resulting usurpation of power by the appetites. By analogy, for Plato, the primary causes of disharmony in the state are ignorance and greed. Ignorance in the Kallipolis will be eliminated by education under the governance of the philosopher king, and greed will be eliminated by outlawing those things which cause men and women to become greedy -- money, property, family. With reason in control, Plato is certain there will be no *stasis* in either the souls of individual men or in the polis.

> Temperance (*sophrosyne*) works in a different way; it spreads literally throughout the whole gamut of the city bringing about the unison -- as in the singing of the same chant -- among the strongest and the weakest and those who are in between.... So we

> are quite right in identifying with temperance this unanimity or harmonious agreement between the naturally worse element and the naturally better element as to which must govern both the state and the individual. (*Republic* 432a)

Thus, for Plato, the healthy psyche is one which operates not only in perfect unity and internal harmony, but does so under the guidance of reason from the rational part of the soul. It is through the control of reason and knowledge that this harmony is to be achieved. This analysis of the soul in *The Phaedo* led Plato to a rather ascetic otherworldly philosophy according to which men go around with their heads in the heavens and their bodies in the tar pits. Plato was certainly an advocate for the life of the mind rather than for the life of the body. He saw the spirit as strong and the flesh as weak. Just as the state is to be governed hierarchically by those with knowledge of the good -- the philosophers -- the psyche was to be ruled by reason.

If we examine Plato's notion of hierarchical control, therefore, we can distinguish two logically distinct elements -- biological health as a lack of *stasis*, and psychological and political health according to which this lack of *stasis* is to be achieved by means of the governance of reason. It is important to differentiate between these two elements of Plato's control theory -- reason and unity. My primary concern, in this chapter, however, is to critically evaluate Plato's notion of biological unity. And so, I will begin by examining how biological unity and regulation is actually achieved absent reason, and, once having done so, I will examine what, if anything, rational control would add to such regulation. In other words, since my quarrel with Plato is with his notion of biological control, I am not concerned, for the moment, with who or what is in control -- the mind, reason, the philosopher king, HAL the computer in 2001, or the cerebral cortex. And so, in order to concentrate on the nature of biological regulation in general, I will, for the time being, skirt the mind-body problem by substituting for the psyche, the activity of the cerebral cortex and the central nervous system acting as a unit. My concern, in this chapter at least, is not with Plato's metaphysics and, only indirectly, with his ethics. Mine is, quite simply, an argument from biology. It rests on our understanding of the actual mechanisms by which the body achieves control, regulation, and stability.

In particular, I will examine Plato's claim that bodily regulation or health is a matter of lack of dissension or divisiveness -- that bodily control is a matter of the elimination of *stasis*. If it can be shown that, on the contrary, bodily regulation is achieved *by means of stasis*, then Plato's use of the analogy from biology in support of a state governed by a *single* or monistic hierarchy will not stand.

Although no scientific argument is entirely empirical, this analysis is not based on competing *models* of biological regulation so much as on the observable mechanisms by which such regulation is achieved. I will show that from a biological point of view, the critical flaw in Plato's thinking is his concept of harmony by means of guidance from a unitary source. Biological regulation, even in a single organism, is not maintained by perfect cooperation between the parts under the guidance of a central controller -- whether that controller is intelligent or otherwise. The regulation and harmony necessary for the health of the body are, in fact, maintained by a multiplicity of feed-back systems usually operating relatively independently of, and in opposition or cross-purposes to, each other. And, although the activities of the whole organism are guided both by genetic plan and, at times, by the central nervous system, the guidance of the central nervous system is usually automatic, or, to use the technical term, autonomic rather than conscious, and the nervous system itself usually operates not as a unit, but as two or more feed-back systems acting at cross-purposes to each other. Therefore, we will see that control in a healthy body is a matter of a balance of power, "checks and balances, forces and counter-forces,"[12] rather than a matter of central guidance and near perfect cooperation between the parts. Moreover, these principles of biological control are essentially similar at *every* level of biological organization, the cell, the organ, the individual, the population, and the ecosystem. Even in the population and ecosystem where there is no guidance from a single set of genes operating within a single body, the mechanisms by which biological regulation are achieved remain essentially similar. It is a theorem of control system theory that complexity is not a function of the inclusiveness level of organization.[13]

Homeostasis

(a) History of the term

What is biological regulation?

A living body must be stable relative to the external environment, but it can maintain its stability only if it is capable of modifying and adjusting to both external and internal stimuli. Thus, there are two very different requirements for the maintenance and governance of a living system -- stability and adaptability. At first glance there seems to be a tension between the two. The more stable a system the less adaptable, and the more adaptable the less stable. William B. Cannon in 1929 coined the term “homeostasis”[14] in acknowledgment of the complex nature of biological balance. The very term "homeostasis" would have been an oxymoron for Plato. A number of Cannon's contemporaries also had difficulties with the word. "Homeo" they correctly interpreted to mean "similar" rather than "same," but "*stasis*" many of them took to mean "static" "immobile" "stagnant."[15] With this term, however, Cannon has, I believe, captured both meanings of "*stasis*" as well as both aspects of biological control -- stability and adaptability. Curiously the term "homeostasis" has survived as a medical term in part because in the attempts to refine the notions by Rosenblueth and Wiener[16] an alternate Greek word meaning "government" was introduced in the 1940s. Rosenblueth and Wiener's term, "cybernetics," is no longer in general use with respect to biological regulation. It was a victim of its own popularity in other fields.

Biological stability, homeostasis, in not what physicists or chemists means by equilibrium. For a physicist something is at equilibrium when it is at rest relative to its environment. When a biological entity is at rest with respect to the external environment it is dead. Life requires constant change and adaptation. If the external temperature rises rapidly, our body must cool itself, and so we perspire. If the external temperature falls we must heat ourselves, and so we shiver and burn more energy. Human beings live in temperatures well below freezing and in temperatures well above 100o F. Nevertheless, internal body temperatures are generally maintained within one or two degrees of an individual's normal bodily temperature in the range of 98.6o F. Deviations of even a few degrees mean illness, and deviations of more than a few degrees will lead to death. If we come into a bright light, our eyes adjust or we are blinded. If we see an automobile bearing down on us at speed, our adrenal glands activate a host of fear-and-flight responses which, once we have responded to the danger, must be brought back into balance. These are obvious adjustments. What is less obvious are the tens of thousands of adjustments the body makes every minute of our lives. To maintain bodily posture alone requires thousands of adjustments a minutes.

> The living being is stable. It must be so in order not to be destroyed, dissolved, or disintegrated by the colossal forces, often adverse, which surround it. By an apparent contradiction it maintains its stability only if it is excitable and capable of modifying itself according to external stimuli and adjusting its response to the stimulation. In a sense, it is stable because it is modifiable -- the slight instability is the necessary condition for the true stability of the organism.[17]

Life requires constant change and adaptation. Life is like dancing a pirouette -- on a tight rope -- in the wind -- while dodging the occasional bullet. Equilibrium is what happens when the dancer falls.

The more evolutionarily advanced the animal, the more numerous, complex, and automatic the regulatory agencies. In man there are physiological homeostatic controls over a very wide range of factors -- from body temperature, to the fluid balance of the eye, to virtually every aspect of blood chemistry. Homeostatic control mechanisms allow the body to function while maintaining a dynamic constancy in what Claude Bernard, the great French physiologist of the 19th century, named the milieu intérieur -- the internal environment. The dynamic stability of this internal biological environment is absolutely necessary for the survival of the system, and it is these networks of homeostatic agencies which provide the biological infrastructure and support not only for our conscious mental activities but also for our ability to rapidly adjust to changes in the external environment.

The ability of an entity to continually respond to and adapt to external stimuli has long been seen as an aspect of any biological life form. Both Braithewaite and Nagel[18] maintain that the concept of system adaptation provides a key to the very definition of life, and also an acceptable framework in which to validate, to the modern philosophical mind, teleological explanations. There is little question that adaptability and, more particularly, feed-back mechanisms which allow for both adaptability and the maintenance of homeostatic control are accepted as characteristic of life forms in general. What is of interest in this discussion is not simply the need for homeostasis to maintain life, but the mechanisms by which homeostasis is maintained. And it is primarily the scientist engaged in medical research, not the philosopher of science, who has explored the *mechanisms* for system adaptation.

(b) The Regulation of Serum Glucose as an Example of Biological Control

The regulation of sugar in the blood, serum glucose, provides an excellent example of homeostatic control mechanisms perhaps because a great deal of research has been devoted to the subject and much is known.[19] Furthermore, because much of this research has been fueled by a desire to improve the treatment of diabetes, the laboratory work has been well-tested by clinical application.

Glucose regulation is critical to survival. Under normal circumstances glucose provides the principal energy source for the brain, and the principle fuel for the central nervous system under most conditions. It is also the preferred metabolic fuel for muscle tissue particularly during emergency situations. Normal, at rest, glucose readings are in the range of 100 milligrams per deciliter of blood (100 ml/dc). During times of stress, elevated activity, or directly after ingesting sugars, serum glucose levels rise very rapidly.

In fear and flight situations glucose levels may shoot up to 400 ml/dc. In fear and flight situations, survival may depend on our ability to suddenly and very sharply increase glucose supply to muscle without diminishing glucose delivery to the brain. In themselves, however, elevated blood sugar levels are dangerous. If glucose levels are not brought, almost immediately, back down to normal levels, the body faces the possibility of diabetic coma. Even elevated blood sugar levels of 180 ml/dc, if prolonged, are dangerous to the body and life-threatening.[20] Since the introduction of insulin therapy most diabetics do not die of diabetic coma, but from those conditions, including heart disease, kidney failure, and blindness, which are associated with *chronic* hyperglycemia. Diabetes Mellitus can be diagnostically defined as fasting glucose levels in non-pregnant adults in excess of 120 ml/dc.

On the other hand, a sustained *drop* in serum glucose to below 60 ml/dc is even more dangerous. Even brief hypoglycemia can cause profound brain dysfunction, and if prolonged, severe hypoglycemia causes brain death. That is, very low blood sugar, results in convulsions, shock, and death. When the body corrects for hyperglycemia it has a tendency to over-correct and fall into hypoglycemia. Even in normal people we experience a burst of energy after ingesting sugar but may some twenty minutes later experience quite the reverse. In the case of the diabetic under insulin treatment, these oscillations can be very extreme indeed, and the diabetic's life is at times as likely to be threatened by insulin shock (very low blood sugar) as by diabetic coma.

Thus, it is clearly essential to maintain glucose levels within certain close tolerances once the immediate need for elevated glucose levels is passed. This is a difficult and delicate task since, for any number of reasons, the body's need for elevated glucose may vary enormously from moment to moment and the need for elevated glucose rarely coincides with periods of carbohydrate ingestion.

How are glucose levels in the blood regulated?

Regulating sugar intake is the one entirely conscious method of regulation of blood sugar. Athletes will quickly ingest sugar drinks during a game and diabetics may carry a supply of orange juice, drinking it when they feel they are in danger of dropping into shock. While minimizing sugar intake may seem a sound preventative health practice for a sedentary population, regulating sugar intake is not normally the primary method for serum glucose regulation. In a healthy person careful monitoring of sugar intake is not necessary, and in a diabetic it is often not, in itself, sufficient to avoid disease and death. In all cases, regulating intake, while not unhelpful, is an exceedingly clumsy means of regulation. The conscious method of regulating blood sugar would work far better if we were all strapped immobilized to hospital beds where both our ingestion of glucose and our need for glucose were fairly constant. Unless a person is in hospital, and linked to an intravenous glucose drip, sugar intake is not constant nor is it timed to the varying needs of the body.

Plato would claim that the knowledgeable doctor could prescribe for the patient the rational or best schedule for ingesting glucose, and the life style best suited to such rational control. But it is on the regulatory mechanisms of the healthy person, and not the diabetic, which he is claiming to model his state, and a healthy person does not require such control by a knowledgeable doctor. In some respects, Plato, with his philosopher king, has modelled his state on the regulatory mechanisms of a diseased body and not on the regulatory mechanisms of a healthy body.

How does a healthy person's body regulate serum glucose? When sugar is ingested there is an almost immediate increase in glucose levels in the blood, but in a healthy individual serum glucose levels do not remain elevated. The glucose is either used immediately as fuel, as in the case of the athlete, or, more likely, it is stored. Most glucose cannot be stored as glucose. The body must convert and store a great deal of glucose, and must be able to retrieve serum glucose slowly during period of fast, and very rapidly during periods of high activity. While the amount and rate of ingestion of sugars is certainly a critical factor for many diabetics, for the healthy persons, glucose regulation is a matter of the movement of glucose into and out of storage as it is required. The primary question for physiologists of the 19th century was where and how is glucose stored in the body, and under what conditions is it released from storage?

Prior to Claude Bernard, it was believed that only plants could create glucose and that therefore any glucose in plasma was a direct product of ingesting sugars. Claude Bernard noted the presence of glucose in the hepatic vein of a dog which had been deprived of dietary carbohydrates for several days. He began a series of experiments which seemed to establish that glucose was stored in the liver as glycogen from whence it could be released into the blood (glucogenesis), and that glucose production continued (gluconeogenesis) in the liver even after glycogen stores had been depleted by prolonged carbohydrate deprivation or by diabetes.

Bernard believed that the storage, release, and creation of glucose was controlled by the central nervous system, but he concluded that the central nervous system was itself functioning as two control systems for the purposes of glucose regulation.

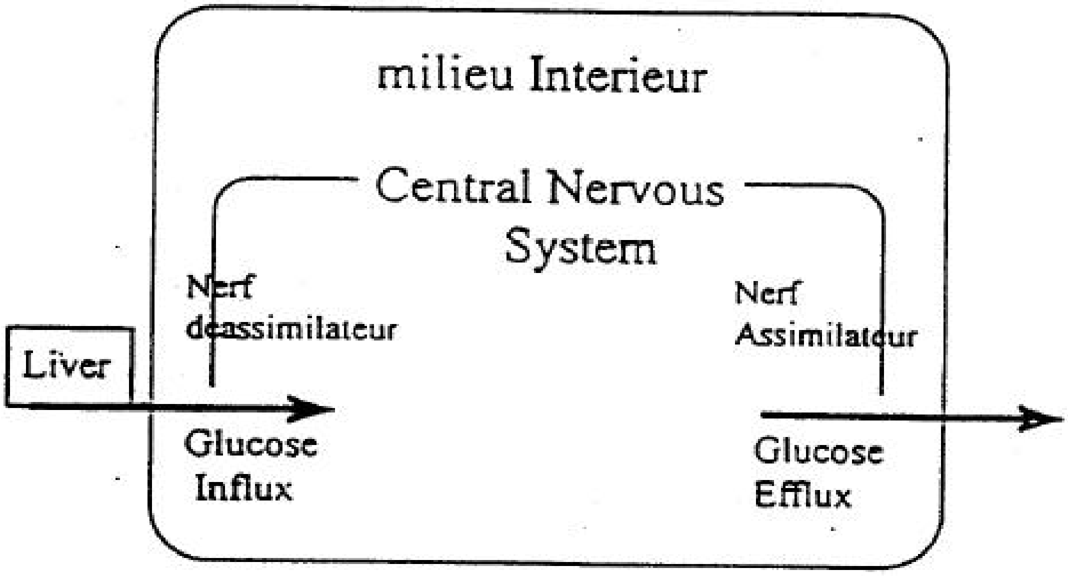

Figure 1

Bernard's famous piqûre experiment convinced him that glucose homeostasis was regulated by a balance of opposing influences originating in the central nervous system and mediated by *nerfs assimilateurs* and *nerfs désassimilateurs*, which exerted respectively anabolic and catabolic influences on glucose metabolism. This was the first suggestion that a Sherringtonian "push-pull" system of biological antagonists might regulate the inflow and outflow of glucose ...[21]

Bernard's understanding of glucoregulation was remarkably prophetic since he died in 1878, eleven years before the role of the pancreas in glucoregulation was discovered, and fifty years before the discovery of insulin by Banting and Best.

William B. Cannon writing in the 1930s helped to develop a more advanced, but still incomplete, understanding of the mechanisms of glucose homeostasis. By the 1930s the nerves which seemed to be responsible for the push-pull mechanisms of glucoregulation had been identified. Cannon knew that stimulation of the pancreas by the right vagus nerve causes insulin to be produced which, in turn, causes glucose to be taken out of the blood and stored as glycogen. And, as Bernard had first noted, stimulation of the adrenal gland by the sympathetic nerves causes glycogen stored in the liver to be converted to glucose and raises glucose levels in the blood. Cannon and the researchers of his generation established that the two nerve systems functioned independently of each other with respect to the regulation of blood sugar. Either system continued to function whether or not the other was in place. In general, the sympathetic and vagus nerves rarely work together.[22] The sympathetic nervous system and the vagus nerves both reacted, independently of each other, to the concentration of glucose in the blood as well as to other stimuli. Notably, of course, the sympathetic nervous system responded to external stimuli in causing the adrenal glands to release hormones. The action of the adrenal glands results in an almost instantaneously elevated blood sugar. In contrast, the release of insulin results in a rapid decrease in blood sugar.

Thus, in establishing the role of the nervous system in stimulating the control of glucose, researchers had identified at least two hormones which were involved in the homeostasis of glucose. Using Bernard's schema these two hormones corresponded to the *assimilateur* and *déassimilateur* functions. Having identified the role of at least two hormones in the control of glucose levels, Cannon investigated the extent to which any neural involvement was necessary to the push-pull homeostatic mechanisms. Cannon established, experimentally, that the mechanisms for the regulation of glucose could operate entirely independently of the nervous system. He was able to surgically remove the sympathetic nerves to the adrenal glands and the vagus nerve to the pancreas and, at least under laboratory conditions, glucose regulation did not seem to be affected. In fact, the experimental animals continued to live for years afterwards. Clearly, under laboratory conditions, chemical triggers to the glands are sufficient to control glucose levels. Once a critical level of glucose is reached insulin is released whether or not there is involvement by the sympathetic and vagus nerves. Thus, while involvement of the nervous system is helpful to glucose regulation, it does not appear to be necessary under laboratory conditions. It might, of course be necessary if the cats were required to hunt in order to live or were themselves subject to attack by predators.

To Cannon the question of humoral as opposed to neural involvement was important. For the purposes of this paper, it is more important to realize that as our understanding of these phenomena grew, the factors and systems which seemed to be operating to control sugar multiplied. It should also be noted that even the involvement of the central nervous system, as postulated by both Cannon and Bernard, does not entail a unitary or centralized control. Cannon characterizes this regulation in fundamentally the same terms as Bernard. Regulation is achieved by two systems working relatively and, at time totally, independently of each other, and in opposition to each other. Each of the hormonal mechanisms seems to respond to chemical changes in the blood and not directly to signals from other hormonal systems.

Both the catabolic and anabolic hormones are in circulation at all times, although the amount in circulation may increase or decrease to meet the regulatory needs. Cannon was well aware that hormonal activity is not unique in this respect. Sherrington developed push-pull theories for muscular control and, as we have seen, neural activity, at least as far as homeostasis of glucose is concerned, is also a matter of a multiplicity of opposing systems. The vocabulary of push-pull, agonist-antagonist, force and counter-force, permeate discussions not only of the endocrine system but also of the neural and muscular control of the body. Furthermore, the physiological analysis in terms of these forces and counter-forces predates by decades any formal mathematical treatment of feed-back control systems.

Certainly with respect to externally generated intruders, the vocabulary of opposition is part of our common language. We know that the presence of toxins often stimulates the production of anti-toxins, and that the presence of foreign bodies may stimulate the production of anti-bodies, but we tend to see these relations in terms of simple cause and effect rather than in terms of systems in opposition. And we tend to see these relations as fundamentally defensive -- the body warding off external threat. The systematic implications are clearer when we look at the body's own agonist/antagonist mechanisms which exist largely independently of external influences. Here we see that not only are the elements which provide homeostatic control acting often in opposition to each other, but that they are generally all in operation, so to speak, at the same time. Thus, it might seem that the pH of blood is maintained at 7.4 in the same way that the pH of hydrochloric acid is maintained by adding to the acid more or less acidic material until the desired pH is achieved in a homogeneously acidic solution. But this sort of uniformity is not present in blood. The pH of our blood is instead maintained by the presence in the blood of both alkalines and acids simultaneously. The pH of the blood is at healthy levels when the overall alkalines and acids are balanced in the degrees equal to produce pH 7.4. The electrolytes, sodium and potassium, are controlled in similar ways. And the calcium level of the body is regulated by means of at least two hormones. The parathyroid gland secretes parathormone (PTH) at a rate that varies inversely with the plasma calcium level. The thyroid secretes another hormone, calcitonin (CT) at a rate that varies directly with the calcium level. Both hormones are present in plasma at normal calcium levels but their effects are antagonistic in that PTH serves to protect against low calcium levels and CT protects against high calcium.[23]

As we shall see, the presence of these systems operating in opposition is not merely an accident of nature. Forces acting in opposition are essential to the maintenance of homeostasis -- indeed for balance in any adaptive feed-back system.

It would be a mistake to dwell on the duality, as opposed to the plurality, of these mechanisms. Biological regulation is not Hegelian. It is not a case of some sort of endocrinological thesis and antithesis resulting in a synthesis which resolves one set of contradictions while perhaps creating others. In fact, in biological regulation there is no synthesis but a continuing dynamic antithesis -- a situation which maintains itself in balance by means of countering forces with opposing forces. And, as we learn more, we see that biological regulation tends to be multifaceted. So, we know now that the metabolism of blood sugar is far more complex than Cannon believed. The hormonal maintenance of this single circulating metabolite, the blood glucose, involves at least ten hormones and six endocrine glands.

Such systems may be hierarchical in organizational structure. It may be the brain which alerts the adrenal gland which activates the release of glucose from storage. But even in the case of hierarchical controls what we see are countering hierarchies interrelating in very complex ways.[24] The relations between the hormones can be additive, cooperative, preparative, or opposing, and it is only by considering the whole system that the process is understood. For example, the conversion of stored glucose in the form of glycogen from the liver and muscle is stimulated by at least four hormones -- glucagon (between meals), epinephrine (particularly in stress situations and for the more effective suppression of insulin, cortisol, and thyroxine). At least four hormones are involved in stimulating the production of glucose from fat and protein -- cortisol, growth hormone, glucagon (which acts here primarily as an insulin suppressant) and epinephrine. Juvenile-onset diabetes, which in its most virulent childhood form is associated with a deficiency of insulin, may be such a threat precisely because while there are several hormones involved in defending the body against the immediately catastrophic effects of low blood sugar levels, insulin is by far the most important hormone depressing blood sugar levels. In a sense, insulin is too important -- too overwhelming a factor. With so much dependent on the activity of this single hormone, the breakdown of biological regulation is more likely -- and diabetes is the result.

If the regulation of glucose is taken as an example of biological governance, then biological regulation is certainly not a matter of hierarchical control in the Platonic sense. It is clearly not a perfect unity among the parts under the intelligent guidance of a system, which, when functioning properly, functions with near absolute unity or harmony. Biological regulation is not achieved in this way.

Would Rational Guidance Improve Biological Regulation?

For the sake of argument, a Platonist might concede that biological controls are not unified, nevertheless, the Platonist would maintain, the body without rational guidance, is at most a very imperfect guidance system. It is imperfect, they might claim, not simply because the controls are not unified but also because the controls, for all animals and for the overwhelming majority of biological human beings are not intelligent and rational. Unified rational or intelligent control would, according to the Platonist, further improve the balance and enhance the unity of the body. Such a Platonic counter-argument deserves careful examination if only because virtually all efforts at social and economic planning in the last century have rested, implicitly or explicitly, on such reasoning. To appropriate John Stuart Mill's language, I have been describing the regulation of blood sugar in a pig. A Platonist might prefer to discuss the regulation of blood sugar in Socrates.

It seems to me that there are two separate questions at issue here for the Platonist. First there is the question of whether intelligent control, in the Platonic sense, would, in fact, improve overall biological performance; and second, there is the question of whether a biological function as ordinary (in the sense that it is shared with virtually all animals and in no sense reflects the potential of the human mind) as control of blood sugar should be taken as our model of biological regulation. All animals control metabolism, but only the higher animals control emotion and conscious thought. It is here in control of our higher functions that the Platonist might argue for a different model of biological regulation.

I believe that Plato himself would have made both of these claims. First, that Socrates, by virtue of his intelligence and rational control, would be better than the pig even at controlling the metabolism of sugar, and secondly, that Socrates, by virtue of his intelligence and rational control, would be more successful overall as an organism than the pig. Reason, Plato would argue, offers a higher form of biological regulation. We can address the second question by answering the first: can the efficiency of biological control systems be increased by rational control? This is not a question of reason supplementing homeostatic oppositional mechanisms, but of reason replacing them.

At first glance the Platonic position seems entirely plausible. For a Platonist who models all knowledge on Euclidean geometry, multiple systems operating at odds with each other are not aesthetically pleasing. There is a certain lack of elegance, in the mathematical sense, a certain confusion, a messiness. At times biological controls seem redundant and wasteful in the extreme. This is particularly true when the body defends itself in what it takes to be emergency situations. In such situations the body works as if the margin of safety is everything -- efficiency and rational economy count for nothing. When, for whatever reason, glucose levels drop below the normal level, the body will begin to consume muscle tissue and even brain cells in order to supply sufficient glucose to the brain to avoid shock. Self-cannibalization is not too strong a word to describe this process. Would central intelligent control of the glucose system be superior in such situations? Would it spare us that?

Although it is in not intuitively obvious we will see that Platonic rationality would not in fact improve the metabolic function of the pig.

The Mathematics of Control Systems

To understand why rational control would, in general, not successfully replace homeostatic biological control, it is helpful to step away from biological systems, the simplest of which are very complex and, for the most part, well beyond the technical scope of existing mathematical techniques, and examine the logic of simple mechanical feed-back systems. In doing so we move from the regulation of biological systems to the general theory of control system mathematics. Biological control theory antedated the formal mathematical theory by many years. Physiologists, at least since Claude Bernard, have realized that biological control was effected by means of systems of complex, interrelated, biological regulators. The mathematical theory was developed in response to the need to understand control systems of antiaircraft guns and guided missiles during WWII. By coincidence Leonard Bayliss, noted physiologist, and son of one of the pioneers of modern physiology, was a key member of the British Army Operational Research Group which worked on these problems of military control systems, and, in particular, the guidance of antiaircraft guns. Bayliss himself, therefore, was in the forefront of research both as physiologist and as engineer. He spoke the language of biology as well as the languages of mathematics, physics, and engineering. He clearly recognized that the mathematics of control system theory could be extended from mechanical and electrical systems to biological systems. He also recognized that even the simplest biological systems are much more complex than physical systems but he, Grodin, Jones,[25] and others in the 1960s and 1970s were convinced that biologists could better understand certain aspects of biological control by examining those aspects in simpler mechanical systems. Throughout this period, therefore, some biologists worked diligently to reduce biological control systems to the equations of control system mathematics although each had to contend with the natural communication barriers between biologists and engineers. Control systems equations may never be able to approximate the enormous complexity of biological control mechanisms, nevertheless, the underlying logic of biological control can be *understood* in terms of such control theory. At the level of purely abstract philosophical theory, control system mathematics is helpful in understanding biological regulation even if the precise equations for glucose regulations may never be developed.

In reviewing the literature, we see that there was a great deal of optimism in the field of control systems theory in the 1960s. This optimism was based not only on recent advances in guidance and control mechanisms, but on the invention and widespread use of the digital computer. Most biological control systems are not linear in the sense that linear means that output is proportional to input. Many non-biological control systems are not linear. To date, there is no general theory for the solution of non-linear differential equations, but it was believed that non-linear systems can be approximated by linear systems. According to Littlewood's pivotal theorems almost every function can be approximated almost everywhere by a continuous function and that almost every continuous function can be approximated by a sequence of increasing step-wise linear functions. Since there is no general theory for solving even linear equations, finding solutions is often a matter of a great many time-consuming computations. With the invention of the digital computer, however, Bayliss and others in the 1960s were convinced not only that non-linear control systems could be approximated by linear control systems but also that finding solutions for these differential equations was simply a matter of computer time. And they assumed once solutions had been found, a theory for finding such solutions would follow. As it happens the computer work which mathematicians optimistically believed would be helpful seems to have established that non-linear systems do not behave like linear systems in some critically important ways. For example, very slight differences in the initial conditions in non-linear functions may lead to infinitely different values. In particular, even very simple non-linear control systems have the capacity for different kinds of instability than do linear control systems. To use the newly coined technical term, non-linear functions may be chaotic. Chaos theory does not disprove Littlewood's theorems it just renders them practically irrelevant in many situations.[26]

While Chaos Theory tended to undermine the development of certain theoretical aspects of the mathematics of control systems, its only effect on the argument in this chapter is to further weaken the case for the Platonists and the planners. If, as we will show, even the simplest *linear* control systems cannot be rationally controlled in the way Plato imagined, it is certainly the case that chaotic functions will be even more resistant to rational or Platonic control.

(a) A Simple Mechanical Feed-back System

Let us consider one of the simplest mechanical feed-back system -- the home heating system. Conceptually there are at least four elements in the simplest mechanical feed-back systems:

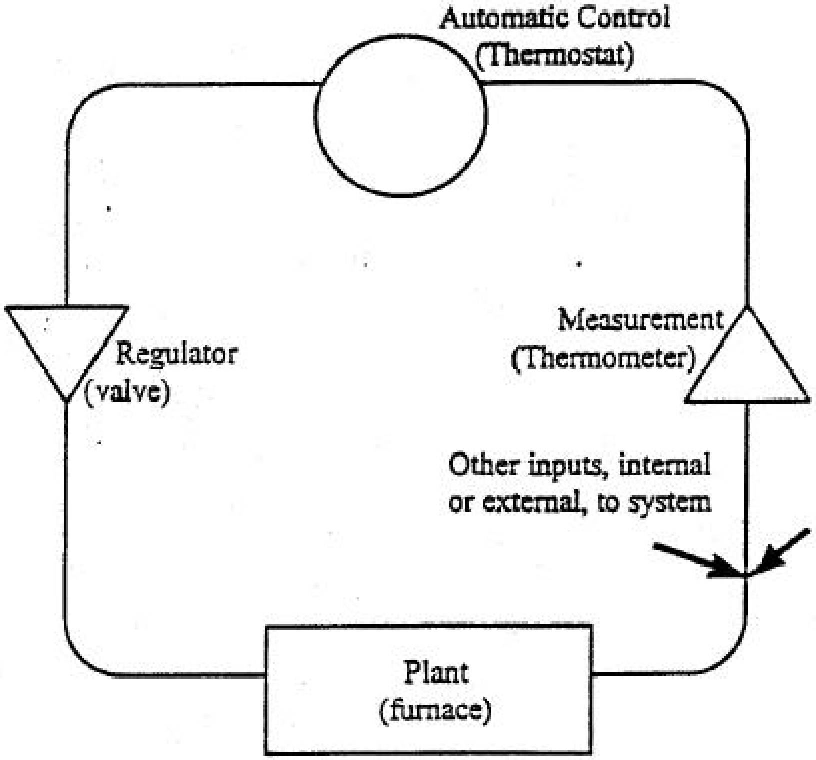
Automatic Control
(Thermostat)
Regulator
(valve)
Measurement
(Thermometer)
Other inputs, internal
or external, to system
Plant
(furnace)

Figure 2

The furnace or plant itself, the thermometer which measures the temperature in the house, the automatic control or thermostat by which a change in the measurement of the temperature activates some sort of regulating valve on the fuel supply to the furnace. In most household systems the thermometer and thermostat are housed in the same unit and the control valve is physically a part of the furnace. But conceptually, at least, it is simpler to think of them as four distinct elements, the plant, the measurement device, the automatic control unit, and the regulating unit. The system is installed for the purpose of holding the controlled condition (the temperature in the house) within some desired range of values. However, there would be no control action whatsoever unless there is a *departure* from that desired range of values. The purpose of the feed-back system is to keep such deviations to a minimum and bring the temperature back to the desired levels as rapidly as possible after there has been a deviation.

We all know how such a system works. If the temperature in the house rises beyond the controlled range, as a result of either internally or externally generated heat, then the thermostat signals the fuel intake valve to choke down, or, in some systems, signals the furnace ignition to disconnect. (For simplicity's sake let us suppose that this is a furnace system with a simple on/off mechanism.) Similarly, if the temperature falls beyond the range, the thermostat reconnects the ignition or the fuel intake valve. For most households this single feed-back system is sufficient to keep the temperature within a desired range. Let us suppose, however, that one requires -- as one might in a large office building with sophisticated computers or as one might in an incubator -- to keep the temperature to within a very narrow range of variation under a great many different conditions. As counter intuitive as it might seem, large office buildings often simultaneously run air conditioning and furnace units. Control is at one and the same time more precise and more efficient if there are two thermostats -- one on the furnace and one on the air conditioner, and if these thermostats operate independently of each other. It is not that both the furnace and the air conditioner are operating under a master plan. The furnace's function is to heat until the thermostat switches it off. The air-conditioners function is too cool until the thermostat switches it off. The result of the operation of both the furnace and the air conditioner is that the temperature is better maintained within acceptable steady-state ranges in the face of a wide range of external and internal shocks to the temperature control system. The temperature control would be further improved if there were automatic light sensors to operate black-out window shades when the sun is hot. It would operate still better if there were automatic heat and wind sensors to operate doors and windows to protect the household temperature from outside changes, and to exploit those changes in the external and internal environment, such as cooking, which might help to maintain temperature at the ideal ranges. With so many censors activating so many mechanisms the resultant heat control system might seem chaotic, inefficient, and, in a word un-Platonic, but we will see that the system, *as a whole,* would work far more efficiently than would the single furnace feed-back loop *if* the primary goal is to prevent and to rapidly correct variations in temperature which might result from changes in either the internal or external environment of the building.

This is the case because of the inherent limiting conditions of control systems in general.

(b) System Lag

In every feed-back control system there are necessary lags. A thermometer does not measure temperature instantly. It depends on the expansion of some mass, and that expansion takes time. We might call this a measurement lag. In control theory it is called a finite lag which means that, measured in terms of the output, the effect of the lag appears all at once.

Furthermore when the furnace is reignited by the thermostat the full effect of that change is not felt immediately. There is what we call a plant lag before the temperature rises. In general, the curve of rising temperature might look like:

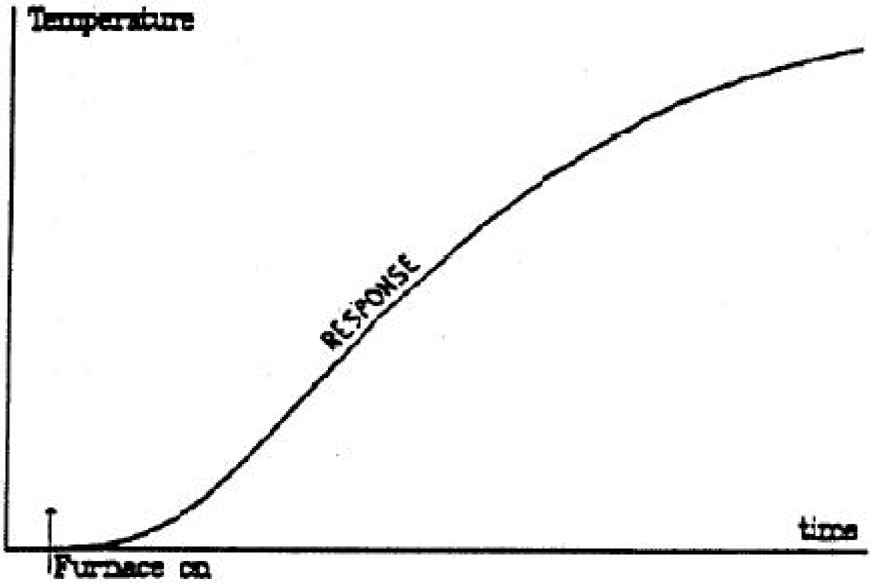

Figure 3

The response is not instantaneous. The initial response is small, and then the actual temperature rises fairly rapidly up to and beyond the range of thermostat settings. The effect of this lag is more gradual and it is called an exponential lag but it is still a lag. Adjustment of the system takes time. It is critical to remember that the thermostat controls the measured temperature and not the real temperature at the instant the furnace is ignited. In any control system it is the *measured* value and *not* the real value that is controlled.

Let us suppose now that with the furnace still on the temperature in the room is at the high setting on the thermostat. As the temperature passes through the high setting on the thermostat, a measurement is taken. But there is a measurement lag before the furnace is actually turned off, and the temperature in the house will continue to rise during that lag-time. There is a further plant lag before the full effects of the furnace disconnect are felt and during part of that time the temperature in the house may continue to rise slowly. Therefore, the temperature in the house peaks not when the furnace is turned off but afterwards -- at a somewhat higher setting.

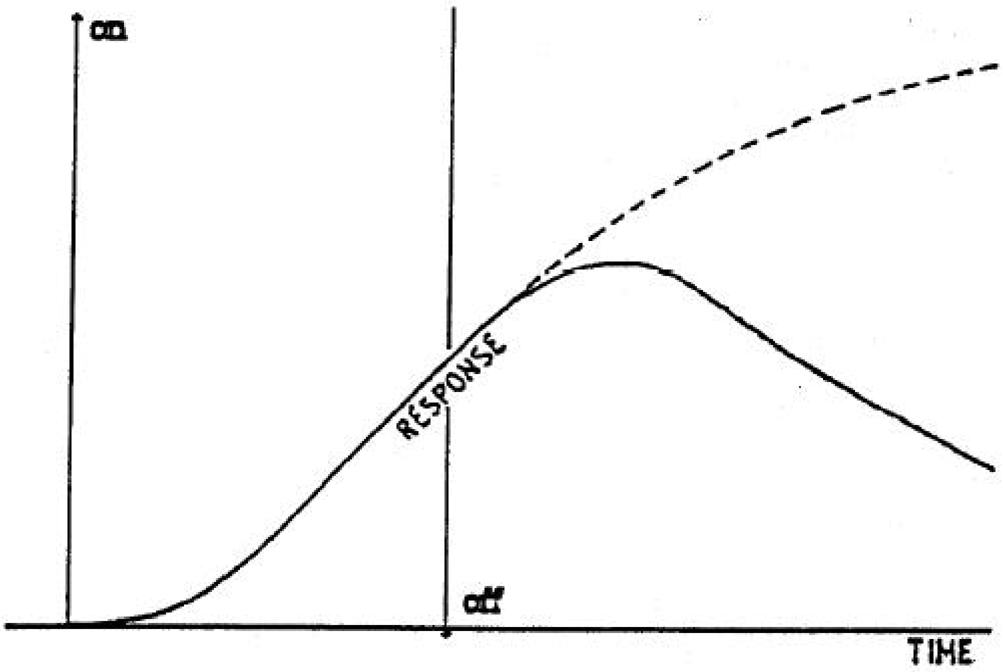

Figure 4

Extending this diagram we see that *even if there are no external or internal changes in temperature* the curve which describes the temperature in the room is out of phase with the theoretical settings on the furnace and the changes are not of the same amplitude.

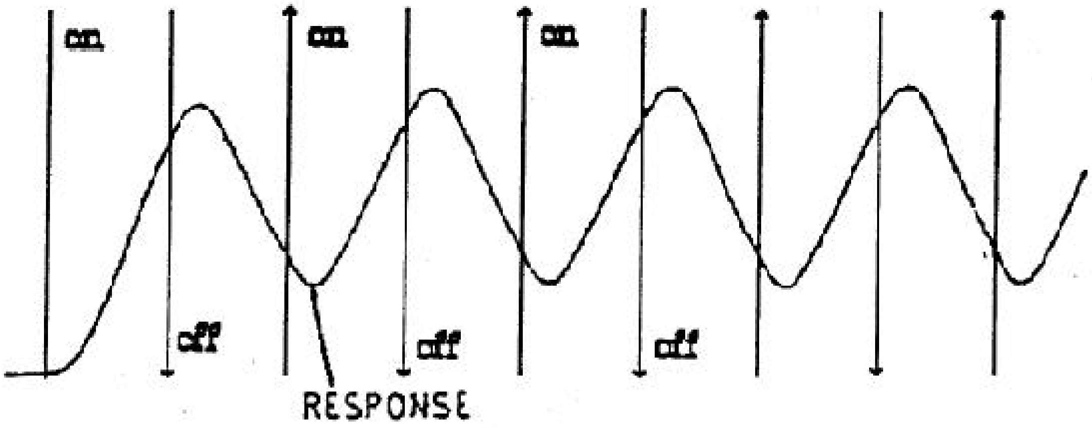

Figure 5

We now have two kinds of errors even in the absence of changing stimuli -- the amplitude of the oscillations, and the time delays introduced by the lags. The system oscillates describing a curve similar to that made by a spring or a pendulum oscillating once put into motion by a force. The ideal Newtonian spring or pendulum, not acted upon by friction, air currents or other "accidents" of nature, would continue to oscillate indefinitely at the same amplitude.

In the home heating system these errors do not seem to cause significant operational problems. We believe we can minimize the effect of these errors by resetting the thermostat. Why not set the thermostat with the error in mind? After all, the purpose of the thermostat is not to go on and off at arbitrarily set intervals, but to control the temperature at or close to a desired value. Theoretically, if we could set the thermostat to turn on and off at that desired level, the curve would seem more acceptable for our purposes. The frequency might be much higher, but the amplitude smaller. Operationally, however, this would not be feasible because the furnace would always be turning off and on. The thermostat must operate on an interval of temperatures -- but why shouldn't we set a very small interval? Again, this might be feasible in a conventional home heating system, but not in a home heating system where massive and almost instantaneous responses might be required. Then, a much larger furnace would be required and either the system would switch on or off well before the massive adjustment could be accomplished, or the furnace would oscillate even more widely like a tight roper walker seeking to regain balance.

To return to the biological example, setting the glucose "thermostat" to very narrow limits might work for the cat in the controlled laboratory conditions but not for a cat living a normal life. That cat requires at least the possibility of rapid and extreme elevations of blood sugar. *The capacity to oscillate is necessary for the cat's capacity to adapt.*

In the case of the furnace we might, as an alternative, choose to set the thermostat so that there would be wide discrepancy between the high and low settings. This might slow the oscillations and, the conservationists tell us, conserve energy. Clearly, the disadvantage here would be that control within a narrow limits would be lost. The cat would be cycling continually between hyper and hypoglycemia.

In general, in all control systems there is a trade-off between steady state control within narrow limits, and the ability of the system to react quickly to rapidly changing inputs. Again, think of a control system as a spring. A stiff spring will have the capacity to bring about rapid and powerful responses to stimuli, but it will also bring about correspondingly dramatic oscillations. How do we preserve the ability of the system to respond to stimuli, and yet return to and maintain a acceptable steady state tolerances?

(c) Lag often Multiply

Even with unacceptable sacrifices in stability and adaptability, we may not have prevented other problems which are associated with lag. Lags multiply. In some circumstances even very small lags may build and critically undermine control unless countered. Again, imagine a simple control situation. Imagine yourself on a highway in heavy traffic. Your goals are to maintain a constant speed as close as possible to the speed limit, and to maintain a constant distance between your car and the car directly in front of you. If the car in front of you decreases velocity, you will decrease velocity as well -- but not quite at the same instant. The interval between the moment when the driver of a motor car sees an obstruction and the moment when he applies the brakes may be about 1/4 second, during which time, if his speed were 60 miles per hour, he would travel about 22 feet.[27]

The example of cars on a freeway is helpful in understanding certain aspects of biological regulation. Think of the highway as a large number of units or cells along which a signal travels. Similarly, hormonal signals move cell-by-cell throughout the body. The mechanism for movement along the "highway" of cells is often diffusion which depends on concentration gradients across cell membranes. Even once in the blood, transmission of a signal is relatively slow. In humans it takes about 10 seconds for a blood-borne signal to travel from our feet to our brain. Neural transmissions are faster than humoral signals, but it is a mistake to assume that nerve signals travel at the speed of electricity or about 300,000 kilometers per second. In fact, nerve signals travel at speeds varying from 1 to 100 meters per second because in order to create the electrical charge in a nerve cell there must be movement of electrolytes across cell walls. There are significant lags at each stage of the transmission of these signals.

Imagine yourself back on the highway. It takes time for sensor cells in the eyes and for the optic nerves, as the measuring devices, to communicate to your mind, as the control device. Your mind, the control device, must then send a signal to the muscles of your legs and feet so that your foot is removed from the accelerator and applied to the brakes. Clearly measurement and control lags are introduced at every stage of the process. Then too, it takes time for the car to decelerate even after you have moved from the throttle to the brakes -- a plant lag. The sum of these lags can prove fatal if the car in front of you stops suddenly. It is not that there is not enough time, and space to stop if they stop.[28] Theoretically, both cars can stop in the same amount of time and the same amount of distance. The collision results only because there is a lag between the first car's and the second car's ability to stop. This is not simply a matter of human error. Even were the two automobiles to be automatically controlled there would be a lag, although it might be less of a lag.

The danger of such collisions is well known to any driver who has managed to pass the written examination for a driver's license. What was less clearly understood until the development of queuing theory in the 1950s and 60s is that this lag builds very rapidly when more than two cars are involved.[29] Suppose that a car half a mile ahead of you slows by two miles an hour. One might think that each of the following cars would also slow by two miles an hour. In fact, each of the following cars slows by somewhat more than the car in front of it, and, therefore, if a car half a mile ahead slows two miles an hour it is not unusual for traffic to slow a very great deal further up the highway if there is only one lane and traffic is near saturation. Now suppose that this is not an open loop but a closed loop highway. Suppose that the highway is like a race track and we are not going from point A to point B but we are making laps. In that case, a car slowing by 2 miles an hour will not only slow all subsequent cars, but it itself will be further slowed as the lag moves along the circuit of the track. In this sense, the lag will continue to build or be amplified until all the cars on the track have come to a stop -- if there is no way to pass cars.

These lag build-ups do not seem to be problems in our home-heating system because we do not ordinarily require of that system a great deal of adaptability and our toleration for temperature difference is considerably greater than our toleration for spatial differences in rush-hour traffic. Besides, as an engineer might point out, there are other methods of control. We need not restrict ourselves to a single clumsy thermostat and an on/off switch on the furnace. For example, we can introduce proportional control into the system. A proportional control rather than simply turning on and off the furnace might adjust a valve to correspond to the difference between the desired temperature and the measured temperature. Provided that there are no external changes, such a proportional control will approach the desired temperature asymptotically, and while it never reaches the desired temperature it will also never overshoot that temperature and should not oscillate. If, however, there are no external inputs there is little or no need for a control system to begin with. Unfortunately, if there is an external stimulus on the system when the proportional control system is very near the desired temperature, like a burst of heat from the cook stove, the temperature will be bumped up past the set value and the proportional control will then be offset. The offset, if sustained or large, will destroy system stability so the offset itself must be corrected. When it is corrected it generally leads to offset in the other direction, and, again, sustained and troublesome oscillations are likely to occur.

There are other methods of control such as integral or derivative controls. But, in general, any *single* method of control suffers from the trade offs between the need to maintain steady state, the need to react to rapid changing circumstances, and the need to avoid unstable and possibly catastrophic oscillations. Therefore, to improve overall control and adaptability it is necessary to *combine* various control mechanisms within a single system. And this is exactly what happens in biological control systems.

In general, in biological systems, as in mechanical systems, control is achieved when signals from several different measuring devices converge on the misalignment of the controlled value. The individual control feed-back mechanisms act to counter each other. In the case of glucose regulation we spoke of agonists and antagonists. In the language of mechanical control theory, we say that system stability is maintained by damping.

(d) Damping

What is damping?

The ideal spring of Hook's law would continue to oscillate at a constant amplitude in a frictionless and gravity-less system. In such an environment steady-state ranges could never be approached after a massive pull on the spring. In the real world oscillations do tend to die down even in systems in which gravity has been neutralized, because there is always friction to damp the action of the spring. Friction keeps springs from the perfect performance postulated by Hook's law. Friction increases as the velocity of the spring increases. Friction in this model is a damping force -- a force which works to counter the original effect of the force on the spring and works in opposition to that force. A damping force is a force which operates counter to the original control mechanism and which is generally activated by the change, or rate of change, in the controlled value rather than by the original control mechanism. In most mechanical systems, particularly in non-control systems, a great deal of effort is devoted to overcoming the effects of friction and thus increasing efficiency.

Friction is one example of a damping force which comes to mind, but friction is by no means the only kind of damping available to the engineer of control systems. The damping of one set of oscillations may be achieved by combinations of other forces, oscillating or otherwise, in the same way that the oscillations in the furnace system are controlled or damped by oscillations in the air conditioning systems, the system of heat and light sensitive windows and window blinds.

Seen through the lens of the classical simplicities of Newtonian mechanics, friction is just "noise" that interferes with the experiment and creates *inefficiencies* in machines. Seen through the lens of control system theory, both biological and mechanical, friction and other damping systems are absolutely necessary to prevent biological and mechanical systems from massive instabilities. Noise is necessary to control. In fact in control theory we do not measure the stability of a control system directly. We measure stability in terms of the ratio of the damping forces to the control forces. In systems which tend to be internally chaotic where error builds on itself very rapidly, damping is probably the *only* means of control. Even in simple linear systems, however, stability tends to be proportional to the amount of damping and inversely proportional to the square root of the gain of the system times inertia and/or lag. In our simple spring system if we imagine a mass attached to one end of the spring, the formula for the damping ratio is:

$$dampingCoefficient = z = \frac{R}{2(KM)^{1/2}}$$

Where R= friction (damping), K= the gain or stiffness of the spring, and M= mass. In general, the equations for stability in terms of damping ratio are: Damping Coefficient

. > 1 over-damped

. = 1 critically damped

0 < . < 1 under-damped

. < 0 unstable

If there is no opposition to a control system it will tend to oscillate widely. If the lag builds, or if another system enhances rather than damps the lags in the original control system, then the damping ratio will go negative and the amplitude of the error will go to infinity or to the physical limits of the system. In each instance, real opposition -- *stasis* -- is the key to the return to and maintenance of system balance. The task of the engineer is not to micro-manage or eliminate oscillations. It is impossible to do either in an adaptive system. The task of the engineer is to build into the design countering or dampening systems which will, under most circumstances, result in acceptable oscillations. In other words, the engineer's task is to design the mechanisms or rules by which the adaptive system is to function rather than to actually design the functioning of the system.

Instability is a constant threat and instability can be fatal. For example in nearly all servo systems the phase lag of the output with respect to the real deviation from the desired control setting becomes progressively more negative as the frequency of the motion increases.[30] Suppose that at some particular frequency the lag is exactly 1/2 cycle. Then the measured quantity of deviation from the desired steady state is always exactly the reverse of the real deviation. The control system will respond not to the real deviation but to the measured deviation. Therefore, in activating the control mechanism it adds error rather than reduces the deviation from the desired control point. The lag causes the controller to get a message precisely the opposite of the message necessary to maintain stability and control. This feature of feed-back systems is put to good use in amplifiers on stereo systems. Imagine a microphone and an amplifier. The microphone speaks to the amplifier which sends the sound back to the microphone and the microphone doubles it on each pass-through until the physical limits have been reached much the same way that the traffic on the highway came to a stop and all control is lost. In control systems, unlike in amplifiers, such error amplification may destroy the system. For example, one method of defeating a guided missile system is to alter the signal from the target more rapidly than the missile guidance system can adjust in order to cause the missile to oscillate until it is driven totally off course. Similarly, the injection of considerable amounts of insulin into the system may result in diabetic coma because the severe and sudden drop in serum-glucose may trigger an equally severe response in the opposite direction. To determine the correct dosage of insulin, particularly in newly diagnosed cases of diabetics, is a delicate process. The doctor, without constant monitoring on the part of the patient, is generally unable to determine the correct dosage. There is no certain formula -- merely trial and error which over the life of the diabetic must be closely monitored. Even then dangerous oscillations will occur. This is not a disease which is cured. It is a disease in which the dangerous effects are moderated.

In biological systems it is essential that oscillations not be allowed to continue unstable. And so, each and every control mechanism must be adequately damped. Thus when the "big guns" are brought out -- for example adrenalin is pumped into the system and glucose levels shoot up -- another control system, independently operated, releases insulin to bring the glucose back into storage. And, simultaneously, less powerful more steady mechanisms are at work to regulate blood sugar. Control is, and must be, achieved then by a number of systems working sometimes at odds and sometimes together to respond to stimuli and to maintain steady state homeostasis.

In biological systems the ability to stay within narrowly defined ranges, or return to such ranges, after extraordinary departures is critical to life. Imagine what the problems of maintaining temperature control of your house would be if the furnace was programmed to suddenly produce hundreds of thousands of BTU within a moment or two whenever certain radio waves reach the house. And then, a moment or two later it was essential to cool the house to avoid a conflagration. Then, turning off the furnace, in and of itself, would be neither fast enough nor powerful enough to control temperature.

(e) Control Is a Matter of Minimizing the Effects of Error and Not Simply of Preventing Error

In a control system error cannot be eliminated, although its adverse effects can be limited. Think of biological control in terms of the woman on the tight rope. She balances herself by oscillating on the rope. The trick is not to eliminate oscillations -- that is technically impossible and may not be desirable. With growing knowledge, it is clear that stable oscillations, like the diurnal cycle, are part of our control mechanisms. The trick is to limit oscillations in such a way that they do not cause the woman to loose her balance. If there is a gust of wind or someone strikes the wire suddenly, the skilled tight rope walker will sway first to one side and then to the other. Unless she is thrown immediately, she is just as likely to fall in the opposite direction to the imposed force because, to begin with, her oscillations will become wider and wider as she seeks to regain her balance. Control is not a matter of eliminating oscillations by fiat -- rational or otherwise. That is not possible. Control is a matter of reducing the amplitude of oscillations to easily manageable proportions.

In summary, some oscillation or hunting occurs whenever there is control action because of the necessary lag in effecting control. There are any number of ways in which the original oscillations can be minimized but each is at some expense to the adaptability of the control mechanism. By and large, oscillations are controlled by the tightrope walker exerting just the right amount of force to counter the oscillations -- in the language of control theory, she may be said to be hunting for the steady state range. We see a similar mechanism at work as we watch a bicyclist loose balance or an automobile skid.

In biological regulation the system is generally damped or controlled by bypassing or blockading the original control action rather than simply by reversing it. If we return to the example of the highway during rush hour, it becomes clear why this is the case. If there is an accident ahead on the one-lane freeway, it is virtually impossible for an ambulance to reach that accident coming from behind. We don't build one lane limited access freeways because build-up and stoppage would be endemic to the system. Introducing a second lane on the highway, even if it is only a passing lane, more than doubles the traffic that the highway will bear. Freeways are multi-laned, there are emergency lanes, hospital helicopters, and, when possible, intersecting roads for emergency vehicles. There are, in other words, alternative methods of access or impacting which do not depend on that one lane of traffic in which the accident occurs. These alternative access systems would not be necessary, if one could predict with assurance the constant speed of each automobile on the road, and if one could be assured that there would be no accidents, slippery roads, sun blinding, excess winds, or any of the other disruptive influences that rush hours are generally heir to. Again, there is no need for control mechanisms when there is no deviation from the controlled value caused by internal or external changes, or when that deviation is entirely predictable. It is not the perfectly regular flow of traffic which requires the alternative systems, but the need of the traffic to accommodate itself to irregularities. What is regular in such systems during rush hour is that there will be irregularities. One can predict that. What one cannot predict is precisely what and where and when those irregularities will occur. That is why the emergency systems and the other drivers respond not as Newtonian billiard balls but as parts of feed-back systems in their own right.

Similarly, the body does not increase blood sugar simply by withdrawing insulin -- that in itself would be far too slow to respond to any genuine emergency. The reasons are clear. First, in the case of biological feed-back systems, the signal is chemical, and therefore it cannot simply be withdrawn. It must be destroyed or self-destruct when it has served its purpose, or the result would be chaotic. Second, and this is true of any signal -- electronic, mechanical, or biological -- the more distant from its source the weaker and slower the signal, and therefore intercepting one set of signals with another set of signals is generally more efficient than initiating change from the original source. Third, as we have seen, the biological signal, or indeed any feed-back signal, initiates a response which is always too late. That is, the correction must always lag behind the situation it is meant to correct. Again, this is true whether the signal is operating in a homeostatic hormonal system or as part of muscular control mechanisms. It is true for mechanical and electronic as well as biological feed-back systems. It will also be true for social adaptive systems where intelligence or the exercise of reason is one of the means by which the system adapts. Due to delays, the corrections will tend to overshoot, both on the high and low side, and the resulting error or oscillation, unless countered, may in itself be unacceptable for the purposes of maintaining biological balance and may even tend to multiply on each completion of a feed-back loop rendering the system unstable. While insulin will remain in circulation, the body also releases and increases the amount of insulin blockers and other hormones in operation which will work to release glucose even as insulin production is halted and the insulin levels are allowed to drop. In general, one of the major distinctions between juvenile-onset diabetes and the so-called adult-onset diabetes is that in the former case there is a deficiency in insulin, while in adult onset cases there may be only a deficiency in the *effectiveness* of the insulin not in the amount of insulin production or circulation. Generally juvenile-onset diabetes is treated with insulin, while only about one quarter of the adult onset diabetics are given supplemental insulin.

An examination of the hormonal systems shows how they are structured to minimize the effect of oscillation. Releasing a hormone into the blood is a relatively slow method of transmitting a signal, but direct neurotransmission of many types of signals to all of the remotely situated cells of the body would require a network of neural connections of such enormous size and complexity as to be infeasible. In contrast to the neural transmissions, all the cells of the body are exposed to the same concentrations of hormones. But the amount of hormone in the blood may be very small -- in the order of a few parts per billion. The hormone acts both as a control signal and, at least in part, as the mechanism for effecting the desired change. To be effective, therefore, the hormonal message must be received by the target cells. The receptor cell must be able to recognize and bind the hormone to it and to virtually ignore other hormones with contrary signals.

In order to effect sudden biological change, hormone effectiveness must be able to rise and fall very rapidly in response to either internal or external stimuli -- much faster than hormone levels in the blood can possibly change. Therefore, the magnitude and the speed of biological effect will depend not only, indeed not even primarily, on the level of the hormone in the blood, but on the target cells responsiveness to the hormone. That is, it will depend on the hormone's effectiveness in reaching the target cells, and effecting or initiating the chemical changes in those cells. Every target cell has receptors which are matched to particular biochemical keys on the hormones like a landing pad on a space station is matched to a configuration on the landing craft, or a telephone is matched to a particular number. The call cannot come through if the line is busy. Blocking – one might say blockading – a hormone at the receptors cells is a primarily method of countering hormonal effectiveness.

Again, the biological terminology is illuminating. The hormone is referred to as the agonist. Once a hormone is bound to a target cell its ability to elicit the biological response is measured. The measure of its effectiveness is referred to as its "intrinsic activity." We arbitrarily assign 100% to the intrinsic activity of the native hormone in situations where it is not countered. The agonists with intrinsic activity less than 100% is referred to as a partial agonist and those with greater are superagonists. Substances that bind but do not activate, thus precluding hormones from binding, are called "antagonists".

Clearly then, if our purpose is to quickly negate the effect of insulin, the inhibition of insulin production would not be sufficient. First, because the insulin already in the blood would remain active; and second because the level of effectiveness of the insulin depends not so much on its concentration in the blood as on the liver cells' receptivity to the insulin.

Thus, a number of mechanisms operate simultaneously, but independently, to reduce the effect of insulin. For example there are chemicals blocking the insulin receptors and thus preventing the delivery of the insulin, simultaneously there will be other hormones working on other cells to effect the release of glucose from the liver and from stored fats, and, if necessary, from proteins. While the body uses any number of methods for control of the hormonal system, it is clear that the introduction of antagonists at the target cell receptors, or the release of other hormones with opposing effects is easily as efficient, if not more so, than the inhibition of the production of the original hormone.

The introduction of antagonists generally comes by means of other hormonal feed-back circuits operating counter to, and *independently of*, the original hormone. The antagonist may be an agonist in its own right. The effect of these antagonistic hormones may also lead to oscillations, but the oscillations of the antagonist will tend to counter the oscillations of the agonist and tend to reduce or damp the amplitude and duration of the total oscillation in the controlled quantity. Again, like friction acting to damp the hypothetical spring, these antagonistic actions may be proportional to the force but, in general, they do not respond directly to the force imposed on the system, but to its effect on the controlled value.

Similar oppositional systems are involved in non-hormonal systems of control -- neural and muscular. In the transmission of nerve signals two chemicals are simultaneously released, acetylcholine and cholinesterase, the first as agonist the second to counter and to destroy the agonist. And the Sherrington push-pull explanation of biological control was not designed to account for hormonal activity but to explain controlled muscle movement. Virtually every movement of the skeletal muscles involves at least two muscles -- one of which contracts and one of which relaxes. And, as I have said, even such a routine muscular activity as maintaining body posture, involves thousands of sensor-initiated adjustments and counter adjustment per minute. Finally, control by means agonists and antagonistic forces is not restricted to the individual organism. It exists at the cell level and at the level of population and ecosystem. Eugene P. Odum's *Fundamentals of Ecology* begins with an analysis of a feed-back loop. These mechanisms are quite clear in the regulatory relationship of predator and prey in biological ecosystems. According to ecological lore, in the 1920s the Arizona Kaibab deer herd was rendered virtually extinct when a bounty was offered on coyote. The thinning of the coyote herd allowed the deer population to grow too quickly for the food supply, and the result was starvation and a rapid decline in the deer population. The coyote are a dampening force to the growth of the deer population. While a Platonist might say that the coyote and the deer cooperate to regulate the deer population, a deer which happens to attract a coyote's appetitive -- if ecologically praiseworthy -- attention, is not likely to view the process in quite so enlightened a way.

Nor does the mathematics of control systems become more or less complex as we pass from discussions of cells to discussions of ecosystems. It is a theorem of control system theory that complexity is not a function of the inclusiveness level of organization. To predict photosynthesis in a single leaf with numerical precision is no more or less complex than to predict, with the same level of precision, photosynthesis for the forest as a whole.

(f) The Extent to Which Intelligence Can Improve Control

In summary, although biological control systems are profoundly more complex than the simple linear systems we have been discussing, the mathematics of control systems is entirely general. A review of the equations (even assuming the input and output are related linearly which they rarely are) is well beyond the scope of this work, but it can be shown that in systems which depend on feed-back, there will necessarily be two kinds of error -- steady state error and oscillations or hunting. Furthermore, the fine tuning of the system to reduce steady-state error will tend to increase the amplitude of the oscillations and these oscillations, if undamped, will become more severe rendering the biological system non-functional. If the systems are not linear, there is the possibility of further irregularities arising from internally generated turbulence or chaos and, in order to maintain biological balance, these too must be damped.

A control mechanism, no matter how brilliantly devised, must be coupled with other control mechanisms acting independently and often in opposition to each other. Without control mechanisms in opposition, control in a feed back system subject to internal and external changes would not be possible. If insulin were the only control of glucose, the body would oscillate wildly between insulin coma and insulin shock -- as may happen when insulin is introduced externally and not as a result of internal homeostatic mechanisms. The introduction of antagonists or dampening counter forces is characteristic of any system which involves controlled reaction to stimuli and in any such system -- mechanical, electronic, biological -- opposing forces are needed to insure control. The mechanic designing a mechanical feed-back system, or the electronic engineer designing an electronic system must design such dampening forces into the system. It is clear, therefore, that the introduction of counter-forces and checks and balances in the biological system is not accidental. It is a direct and necessary result of the two conditions of a living system -- stability and adaptability. It follows that in so far as a political system is analogous to a living control system -- that is, in so far as it is capable of stability and adaptability, it too will depend on force and counter force, checks and balances.

Oppositional control -- in a word *stasis* -- is the *sine qua non* of stability in feed-back systems. No planner, or engineer, or social planner, or philosopher king, no matter how knowledgeable or powerful, could build a stable adaptable system without allowing for the *free* interplay of force and counter-force – of *stasis*. While a knowledgeable engineer may be able to predict the range of stimuli and situations requiring responses, no engineer can predict the moment-to-moment occurrence of stimuli. If he could, it would not, *by definition*, be a control system.

Reason

Intelligence and reason in the sense of conscious calculation of ends and the means to achieve those ends, serves as a form of control in human adaptive systems. Indeed, as Peter Godfrey-Smith and others have claimed cognition itself is a "highly developed homeostatic device."[31] Viewed from this perspective, the primary function of cognition, in any form, is to enable the agent to deal with its environment. Our ability to learn and to reason is an extraordinarily powerful tool for survival, conscious intelligent or rational control is relatively slow, relatively clumsy, and, like other very powerful adaptive mechanisms, conscious reasoning may be error-prone in comparison to that multiplicity of systems and counter-systems which govern even the simplest of biological and human systems either automatically or habitually. If, in order to maintain the balance on our tight rope, every message must be transmitted to the cerebral cortex, processed intelligently, and reflected on, we would begin to oscillate widely and we would fall. Instead, biological balance is largely maintained by a very large number of very small automatic adjustments and counter-adjustments. Intelligence is often too slow. As an adaptive tool, it has proven most successful in inventing tools and bringing about technological change. It has not proven particularly successful in biological regulation. In a biological crisis a person with "split second instincts" has a better chance of survival than does a mere philosopher.

As a species we can afford sluggish regulatory decision making only for conscious mental decisions, and then we can afford delays at least in part because we are able to rely on automatic and complex controls to maintain the balance of the system as a whole.

Moreover, the exercise of intelligence is itself more complex than the simple notion of calculation might suggest. We do not simply climb out of the cave of ignorance and see the truth. Intelligence does not function in monistically straightforward ways -- even within the mind of a single individual. We can think of our various modes of knowledge or science as themselves being singly and collectively adaptive systems. As pragmatists like Quine have argued, a human beings' knowledge should itself be thought of as an adaptive system -- although a relatively slow adaptive system. As an adaptive system, our system of knowledge, like our maintenance of blood glucose levels, is underdetermined by external phenomena. It must square with external reality in places, but not in all places. Like any adaptive system it strives to maintain an internal equilibrium even in the face of external challenges. It is a homeostatic system. From our discussion of homeostatic systems, we can infer that a successful knowledge system must be capable of quickly adapting and assimilating shocks to the system, but it must also do so without itself going into shock. Since we reason in terms of these knowledge systems, reason is not simply a black box into which we feed in-puts and out of which we are served a definitive out-put as some rationalists and early proponents of artificial intelligence would have us believe. In so far as conscious rational control is itself dependent on feed-back data, as it generally is, there will be steady-state error and oscillations in our reasoning. This is true of knowledge at the individual level and of knowledge in the polis as a whole. If a unihormonal feed-back circuit is unable to maintain glucose within narrow tolerances and without catastrophic oscillations, then a central planner, no matter how intelligent, or rational, or knowledgeable is unlikely to perform satisfactorily in controlling most functions of the body politic. Instead, it is more truly rational to suppose that social and economic balance, like biological balance, is best maintained by a very large number of very small unconscious adjustments and counter-adjustments. It will be better maintained in a social system with relatively many decision-makers or decision-making sub-systems than in a system with only a single decision-making entity no matter how benevolent and intelligent the decision-maker is.

The implications of this interpretation of bodily health for the analogy between the health of the body and the health of the state are the subject of another chapter, but it should now be clear that, even were we to accept that the health of society is analogous to the health of the body, we would not arrive at Plato's design of the healthy society. Therefore, even if we accept the analogy, we would be forced to reject Plato's conclusions.

If political health is matter of *stasis* -- checks and balances, forces and counter-forces, coupled oscillations, -- then any Platonically planned economic or political system, no matter how rational and how intelligently formulated, is bound to fail. A healthy society would then be one in which the control and balance critical to survival would be maintained by means of largely automatic and complex systems of force, counter force, of coupled and competing hierarchies, of checks and balances. Such a social system must, if it is working correctly, have the ability to rapidly adapt to extreme situations like war or crop failure. As in the case of biological regulation of blood sugar, however, any severe damage to the *underlying* automatic homeostatic mechanisms might have indirect but nevertheless catastrophic implications for the survival of the political body. At least in this one sense, a social philosophy based on the biological analogy would argue against sudden revolutionary societal changes -- including those designed to accomplish total "rationalization" of the system.

In the first chapter, I argued that such a rationalizing of the polis into a single consistent system would deny us many of our most cherished values, our right to choose the good, and so our humanity. Here I have argued that such a Platonically rational system would necessarily fail even as a method of regulation for a community of robots.

To the extent that the state is indeed the body writ large, the state will not be Plato's monistic Kallipolis.

Although perhaps not a community of atomistic individuals, a healthy polis, on *this* analogy would be liberal in that it would tend to support the ideals of a relatively open society rather than a relatively closed society, a relatively pluralist society in which individual human beings and human organizations would be free to work largely independently pursuing their own visions of the good, a relatively free market with more decision makers rather than the planned economy with a single philosopher king no matter how knowledgeable. It would, at the same time, be a somewhat conservative society. The men and women of such a polis would recognize the importance of maintaining the largely invisible homeostatic mechanisms of society. Reform is possible but in order for their to be successful reform the underlying homeostatic mechanisms must be protected from rapid and revolutionary change. Homeostatic mechanisms are complex and evolve slowly over time. They are relatively simple to destroy, and very difficult to create.

Our guides to such a society would not be Plato, Rousseau, Marx, or even Hobbes. They are more likely to be Adam Smith, Edmund Burke, and James Madison. And our model for political dialogue would not be *The Republic*. A far better model for political dialogue would be that debate of ideas and interests that resulted in the drafting and the ratification of the Constitution of the United States and the Bill of Rights.

Endnotes

1.See John Wild, *Plato's Modern Enemies and the Theory of Natural Law*.

2. The English philosophers, even Hobbes whose image of the Leviathan is, quite literally, a composite of many individuals, seemed to have realized the limitations of such an analogy. Conceptually, Hobbes' individuals cede virtually all their rights to the sovereign for self-protection. They do not dissolve their wills or their selves into the sovereign. By and large, the English philosophers understood that the state is not a unit in the same way that the individual is a unit -- society in not the soul writ large. The needs, rights, and individuality of its people cannot simply be dissolved into the perceived needs of the state.

3.Liddell and Scott. *An Intermediate Greek-English Lexicon.*

4.See *The Republic* 422a, 422e-423d, 424b-e, 545c-d, 547a, 412e-414b.

5.H. D..P Lee, introduction to his Penguin translation of *The Republic*, p. 31.

6.Nicholas White, *A Companion to Plato's Republic*, p. 15.

7. John Winthrop, "A Modell of Christian Charity," published in *Early American Writing*, p. 110.

8.Engels writes in *Herr Eugen Duehring's Revolution in Science* (1878) (*Anti-Duehring*) that when the proletariat seizes power and takes ownership of the means of production "It puts an end to itself as the proletariat, it puts an end to all class differences and class antagonisms, it puts an end also to the state as the state." Plato himself does not use "*stasis*" when discussing class in *The Republic*. Technically, for Plato there are no classes in the Republic -- only "kinds" of people.

9.Karl Popper, *The Open Society and Its Enemies*, p. 173.

10.As quoted in E. F. Adolph, "Early concepts of physiological regulations," p. 739.

11.Plato uses "*eunomia*" throughout *The Republic*. It is noteworthy, however, that he uses "*isonomia*" a term strongly associated with Athenian democracy only in a quasi-humorous discussion of the community of wives.

12.Eugene P. Odum, *Fundamentals of Ecology*, p. 5.

13.Odum, p. 6.

14.Walter B. Cannon, *The Wisdom of The Body*.

15.Richard W. Jones, *Principles of Biological Regulation, An Introduction to Feedback Systems*, p. 5.

16. N. Wiener, *Cybernetics*.

17. Charles Richet *French Dictionary of Physiology* 1900 as quoted in Cannon, *The Wisdom of The Body*, p. 21.

18. R. B. Braithwaite, *Scientific Explanation*, Chapter 10, and Earnest Nagel, *The Structure of Science*, Chapter 12.

19. In this discussion of glucose metabolism in addition to Cannon, I rely on material from: Roger H. Unger, "Concepts of Glucoregulation: From 1878 through 1978." *Claude Bernard and the Internal Environment: A Memorial Symposium* (1978); *Williams Textbook of Endocrinology* (1985); and Mayer B. Davidson, *Diabetes Mellitus: Diagnosis and Treatment* (1991).

20.The most common damage is in the creation of abnormalities in walls of both the large and the small vessels of the vascular system. These changes in the large vessels may cause cerebral vascular accidents and myocardial infarctions. Diabetics are very much more at risk in these categories. Changes in the small vessels are associated with damage to the retina and the kidneys. Since the introduction of insulin therapy in 1922 most diabetics do not die as a result of diabetic coma, but as a result of vascular complications which do not develop until many years after the onset of diabetes mellitus. (Davidson, p. 18)

21.Unger, p. 54.

22. In general, the sympathetic and vagus nerves each operate autonomically without direction of the cerebral cortex in regulating the smooth muscle and glands of the viscera. Each of the glands and organs of the viscera are supplied by nerves from at least two sources, and, as a rule, these two sources are opposed in their effects. For example, the vagus slows the heart and the sympathetic accelerates the heart; the vagus decreases glucose concentration in the blood and the sympathetic increases glucose levels. Opposition is intrinsic to the body.

23. Richard Jones, *Principles of Biological Regulation*, p. 270-271.

24. Richard Jones, *Principles of Biological Regulation*, p. 285. This discussion of organization in terms of relatively independent hierarchies is reminiscent of Michael Walzer's *Spheres of Justice*.

25. In the discussion which follows I am largely indebted to Bayliss, Jones, and Grodin for the discussion of biological control theory and to Farringham for the discussion of control systems mathematics in general.

26. Chaotic functions may still be approximated step wise by linear functions, but the calculations necessary to do so, might take our fastest computer millions of years to complete.

27. Bayliss, *Living Control Systems*, p. 34.

28. We imagine that such collisions do not occur in the case of railroad operations which are centrally controlled, but the reason they do not occur is that the railroad is designed never to encounter rapidly changing external situations. By design the railroad is not a very adaptive system. Thus, when and if the signals fail on a railroad or unanticipated events occur on the track, there is almost no possibility for the engineer to avoid disaster.

29. Again, advances in this theory were to some extent a by-product of advances in engineering. The problems associated with the build-up of delays in a queue began to be studied seriously only when actual traffic flows on the first restricted-access highways proved to be much less than projected flows had been.

30. Bayliss, *Living Control Systems*, p. 61.

31. Peter Godfrey-Smith, *Complexity and the Function of Mind in Nature*, p. 76.