The Raison d'Être of Secondary Plant Substances

These odd chemicals arose as a means of protecting plants from insects and now guide insects to food.

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It has been stated that living plants, especially the flowering plants, furnish the food materials for fully half of the living species of insects. Every part of the plant may be eaten, but green leaves no doubt constitute the bulk of vegetable food material. Since leaves are the principal food of insects, and in most cases the only food, it is obvious that they must contain all the food materials which an insect requires. Yet we find that most insects that eat leaves are more or less selective in their choice of food plant. Insects may feed on only one species or on a few closely related plant species (monophagy), on a larger group usually confined within a certain plant family (oligophagy), or on a still wider group of plants (polyphagy), but they never feed on all plants. Is host selection in this group of insects governed by the nutritional superiority of the particular plant or region of the plant that serves as a food, or rather by the presence or absence of attractants and repellents in plants which are otherwise of more or less uniform food value?

The basic food requirements of all insects seem to be very similar and very much like those of higher animals. They include the "essential" amino acids, most of the vitamins of the B group, a sterol, and the physiologically important minerals. The nutritional requirements of plant-feeding insects are not known in most instances, but there is no reason to assume that they differ from those of other types of insects which have been more extensively studied. These basic requirements of insects concern substances which occur in *all* living cells, including, of course, those of plant tissues. Insofar as the occurrence of these substances is concerned, the composition of all leaves is very much alike, and there is little reason to suppose that differences in chemical composition with respect to the "primary" substances (which occur in all living matter) can be responsible for the choice of food plant on the part of the insect (*1*).

Plants also contain a vast array of what have been called "secondary" plant substances (*2*). These may be conveniently grouped as glucosides, saponins, tannins, alkaloids, essential oils, organic acids, and others, many thousands of which have been described in the literature. Their occurrence is sporadic but may be specific for families, subfamilies, and genera and sometimes even for species or subspecies. Their role in the metabolism of plants has never been satisfactorily explained, but in view of their sporadic occurrence and of the differences in their chemical constitution, it is almost inconceivable that they play a function in the basic metabolism of plants. For the same reasons, it is also highly improbable that they are of nutritional importance for the insects in the same sense as the "primary" substances are—namely, that they are metabolized and utilized in tissue synthesis.

It is suggested that the food specificity of insects is based solely on the presence or absence of these odd compounds in plants, which serve as repellents to insects (and other animals) in general and as attractants to those few which feed on each plant species. The immense variety and number of compounds concerned thus corresponds to the equally immense variety of specific nutritional relationships between insects and plant hosts. The compounds concerned need not play any role in the basic metabolism of either the plant or the insect, since they serve merely as trigger substances which induce, or prevent, uptake of the true nutrients. Most, if not all, secondary plant substances possess characteristic odors or tastes and thus may elicit sensory reactions to the food. In contrast, most of the important nutrients, like proteins, starch, fats, vitamins, or minerals have little or no taste or smell, at least not at the levels at which these nutrients are present in plants.

It is suggested, then, that leaf-feeding insects could develop equally well on any leaves, provided they ate enough of them. We must assume that early in their evolution plants developed the characteristics which made them unpalatable to the rising multitude of insects. The unpalatability was accomplished by the production of the vast array of chemical compounds which characterize specific taxonomic groups of plants. In fact, the appearance of the flowering plants in the early Cretaceous coincides with the various morphological and physiological adaptations in both insects and plants which characterize the interdependence between the insects and the flowering plants. This reciprocal adaptive evolution which occurred in the feeding habits of insects and in the biochemical characteristics of plants forms a striking parallel to the better understood relationship between the shape, color, and scent of flowers and the sensory responses of insects. It is common knowledge that the pigments and flavoring substances of blossoms owe their existence solely to their functions as attractants for insects. Is it less logical to assert that the secondary substances in plants exist solely for the purpose of repelling and attracting insects?

Had the plants been entirely successful in developing their chemical protection against insects, there would be no insect problem in agriculture. In fact, however, insects on their part responded to this chemical control of the plant. A host preference arose when a given insect species, by genetic selection, overcame the repellent effect of such a material, thereby gaining a new source of food. This led to a situation where further selection produced new species or genera of insects that require the former repellent as an attractant to induce feeding.

To establish the ecological relationships between insects and secondary plant substances, the following points should be considered or proved. (i) The active substance should be isolated and

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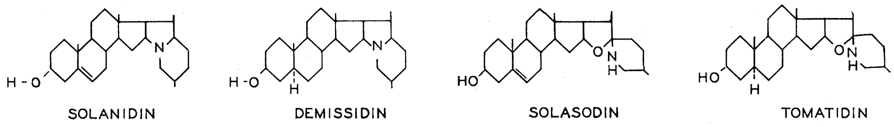


Fig. 1. Chemical structures of four aglycons.

identified. (ii) The isolated compound, if an attractant, should induce feeding when applied to leaves which are not commonly accepted as a food by a certain insect, or when incorporated in neutral media like filter paper or agar jelly. (iii) Members of plant families other than those which commonly contain the attractant in question should be acceptable if they normally contain this compound. (iv) A quantitative relationship should exist between the concentration of an attractive substance and feeding response. (v) A compound which serves as a repellent in a particular insect-plant relationship should, when incorporated in the normal food plant, make it unattractive. (vi) A plant may be attractive and at the same time poisonous, either through possessing separate attractive and poisonous compounds or through presenting these two effects in one and the same compound.

In the following paragraphs the situation as it has emerged for some of the principal plant families—Cruciferae, Umbelliferae, Solanaceae, Leguminosae, Moraceae, and Gramineae—will be discussed.

Cruciferae

All members of this family contain glucosides with a mustard oil as the aglycon; some of these glucosides, like sinigrin and sinalbin, are widely distributed. Cruciferae have a very characteristic fauna of lepidoptera, flea beetles, and aphids. The first detailed description of a chemical insect–host-plant relationship concerned the work of Verschaeffelt (*3*) on the white cabbage butterflies *Pieris brassicae* and *P. rapae,* which feed almost exclusively on members of this family. Forty years later, his work was largely confirmed and was extended to the diamondback moth *Plutella maculipennis* by my collaborator, Thorsteinson (*4*). These insects feed exclusively on Cruciferae and a few species of other plant families which contain similar glucosides. Many other plants were eaten by *Plutella* but only after they had been treated with sinigrin or sinalbin. A quantitative relationship exists between the glucoside content of the food and the feeding response of *Plutella.*

Table 1. The inhibitory action of a number of alkaloids from Solanaceae on potato beetles, in relation to the composition of the sugar component and the structure of the aglycon (Fig. 1). [After Schreiber (*8*)]

Degree of inhibition	Glycoalkaloid	Plants of origin	Sugar component	Aglycon	Double bond in aglycon
++++	Tomatin	*L. esculentum*	Tetrasaccharide with xylose	Tomatidin	Absent
++++	Demissin	*S. demissum*	Tetrasaccharide with xylose	Demissidin	Absent
++++	(Tetrasid)	*S. polyadenium*	Tetrasaccharide with xylose	Tomatidin	Absent
+++	(Tetrasid)	*S. schreiteri* and *S. punae*	Tetrasaccharide with xylose	Solanidin	Present
++	(Triosid)	*S. polyadenium*	Trisaccharide with xylose	Tomatidin	Absent
++	Solacaulin	*S. acaule* and *S. caulescens*	Trisaccharide with xylose	Solanidin	Present
++	β-Tomatin*		Trisaccharide without xylose	Tomatidin	Absent
++	β-Demissin†		Trisaccharide without xylose	Demissidin	Absent
+	Dihydro-α-solanin‡		Trisaccharide with rhamnose	Demissidin	Absent
–	α-Chaconin	*S. chacoense* and *S. tuberosum*	Trisaccharide with rhamnose	Solanidin	Present
–	Solamargin	*S. nigrum, S. sodomeum, S. aviculare,* and *S. auriculatum*	Trisaccharide with rhamnose	Solanidin	Present
–	Solasonin	*S. nigrum, S. sodomeum, S. aviculare,* and *S. auriculatum*	Trisaccharide with rhamnose	Solanidin	Present
–	α-Solanin	*S. tuberosum*	Trisaccharide with rhamnose	Solanidin	Present

* Prepared by partial hydrolysis of tomatin; † Prepared by partial hydrolysis of demissin; ‡ Prepared by hydrogenation of solanine.

Umbelliferae

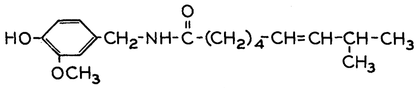
This family is characterized by the presence of essential oils, many of which are known as constituents of spices. According to the investigations of Dethier (*5*), *Papilio ajax* was found feeding on 18 different plants of this family, containing any of the following crude oils: carrot, caraway, anise, coriander, celery, and angelica. Pieces of filter paper treated with such oils or with pure constituents of oils, such as carvone (from caraway), methyl chavicol (from anise), or coriandrol (from coriander), were also attacked. Methyl chavicol is also contained in certain nonumbelliferous plants (Rutaceae: *Dictamnus fraxinella*; Compositae: *Solidago* sp. and *Artemisia dracunculoides*) which are eaten by this insect.

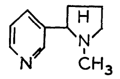
Leguminosae

The Mexican bean beetle, *Epilachna varivestis,* feeds almost exclusively on plants of the genus *Phaseolus* but has, in recent years, become increasingly adapted to the soybean in the United States. It never feeds on *Vicia faba.* Evidence points to the effect of a glucoside of the nature of a triterpenoid saponine as the attractive factor. This compound has been concentrated but not yet isolated (*6*).

Solanaceae

The very extensive work of Kuhn, Schreiber, and others on the structure and occurrence of glycoalkaloids in Solanaceae and their effect on the potato beetle *Leptinotarsa decemlineata* has been summarized by Kuhn and Löw (*7*) and by Schreiber (*8, 9*). These alkaloids, contrary to former expectation, do not make the plant attractive to the beetles but are the agents which render a species of Solanaceae repellent or toxic. The compound which makes the potato plant attractive to *Leptinotarsa* has never been identified. Glycoalkaloids of related structures occur in Solanaceae in an astonishing diversity of structures, those occurring in the common potato plant, solanine and chaconine, being harmless and of no apparent effect on the potato beetle, and those in other plants—for example, in tomato, *Solanum demissum, S. chacoense,* and tobacco—being repellent and sometimes toxic. Schreiber (*8*) attributed the adversely acting properties to the lack of the double bond in the aglycon, to the tetra- (as against the tri-) saccharide component, and to the presence of xylose (Table 1 and Fig. 1). The following were recognized as repellent compounds in other Solanaceae: tomatine (in tomato), the "leptines" in *S. chacoense* (Kuhn in *10*), soladulcin and *S. dulcamare* (*8*), a tetrosid in *S. acaulia* (*8*) (Table 1), and compounds of an entirely different structure, such as the burning principle of red pepper, capsaicin (in *S. capsicum*), and nicotine in tobacco (*8*).


Capsaicin


Nicotine

One of the most striking demonstrations of the repellent effect of nicotine on the potato beetle is presented in certain grafting experiments. It is well known that nicotine in tobacco is synthesized in the root. A tobacco plant which is grafted on a potato root is free of nicotine and is eaten by *Leptinotarsa.* Conversely, a potato plant grafted on a tobacco root becomes fully resistant (*11*). *Petunia* and *Salpiglossis* are attractive to the beetles and, at the same time, highly toxic (*12*).

Table 2. Feeding and growth responses of the tobacco hornworm to various plant materials. [Data from Yamamoto (*13*)]

Plant	Common name	Acceptability*	Support of growth†
	Group A. Solanaceous plants		
Lycopersicon esculentum	Tomato	+++	+++
Datura stramonium	Jimson weed	+++	+++
D. stramonium tatula		+++	+++
D. innoxia		+++	Not tested
D. wrightii		++	++
Lycium halimifolium		+++	+++
Nicotiana tabacum	Tobacco	+++	+++
N. affinis		+++	+++
N. rustica		+++	+++
N. suaveolens		+++	+++
Solanum nigrum	Black nightshade	+++	+++
S. rostratum	Buffalo bur	+++	+++
S. carolinense	Horse nettle	+++	+++
S. tuberosum	Potato	+++	+++
S. dulcamara	Deadly nightshade	+++	+++
S. melongena	Eggplant	++	Not tested
Physalis virginiana	Ground cherry	+++	+++
P. heterophylla		+++	+++
P. alkekengi		+++	Not tested
P. ixocarpa	Tomatillo	++	Not tested
Nicandra physalodes		+	+
Petunia hybrida	Petunia	+++	– – – –
Capsicum annuum	Green pepper	++	++
Browallia americana		+++	Not tested
Brunfelsia americana		+++	Not tested
	Group B. Nonsolanaceous plants		
Lactuca sativa (Compositae)	Lettuce	++	+
Brassica oleracea, var. *capitata* (Cruciferae)	Cabbage	++	+
Phaseolus spp. (Leguminosae)	Green bean	–	–
Ipomea purpurea (Convolvulaceae)	Morning-glory	–	–
Ulmus americana (Ulmaceae)	Elm	–	–
Quercus spp. (Fagaceae)	Oak	–	–
Catalpa spp. (Bignoniaceae)	Catalpa	–	–
Morus spp. (Moraceae)	Mulberry	–	–
Plantago spp. (Plantaginaceae)	Plantain	–	–

* (+++) Readily acceptable; (++) acceptable after 2 hours of contact; (+) acceptable after 8 hours of contact; (–) rejected; (– – –) toxic effect.

† (+++) Normal growth; (++) slow growth and low mortality; (+) slow growth and high mortality; (–) nonsupport of growth; (– – –) premature death.

By contrast, the most efficient food plants of the tobacco hornworm *Protoparce sexta* are tobacco and tomato. This insect feeds widely, however, and almost exclusively, within the family Solanaceae (Table 2). A substance attractive to this insect and found in plants of this family, of the nature of a glucoside but not containing an alkaloid, has been isolated but not yet identified. This substance also appears to be attractive to the potato beetle. *Petunia* is also eaten by this insect, with toxic effects (*13*).

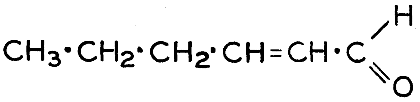
Moraceae

The relation of the silkworm *Bombyx mori* to its food plant, the mulberry tree, *Morus alba,* has long been claimed as one of the most striking examples of monophagy. Yet this insect is known to be capable of feeding not only on a number of other Moraceae, such as several species of *Cudrania, Maclura, Broussonetia,* and *Ficus,* but also on several Compositae, such as lettuce, dandelion, and *Scorconera.* A great deal of evidence to this effect is presented by Tanaka (*14*). Hitherto emphasis has been placed on the fact that the silkworm feeds on substitutes for *Morus* for only short periods, or that the various substitutes are otherwise inferior to *Morus.* From the point of view of food specificity, however, all positive reactions of the silkworm to other plants, independent of the ultimate result, are highly revealing.

Evidence has been presented by Watanabe (*15*) to the effect that silkworms are attracted to many different plants from a distance; some of these (such as mulberry) are then eaten, while others (soybean and tea) are not, while other plants, such as fig and lettuce, though not so attractive from a distance, are often eaten to some extent. The attractive principle has been isolated from a steam distillate of many plants and identified as β-γ hexenol and α-β hexenal (*16*). These compounds are

$$CH_3 \cdot CH_2 \cdot CH{=}CH \cdot CH_2OH$$

β-γ HEXENOL (LEAF ALCOHOL)



$$CH_3 \cdot CH_2 \cdot CH_2 \cdot CH{=}CH \cdot C\overset{H}{\underset{O}{\diagdown}}$$

α-β HEXENAL

Table 3. Degree of feeding by larvae of the silkworm *Bombyx mori* on various plants of the family Moraceae and the effects of such feeding with respect to growth and survival of the larvae. The degree of response is expressed by a graded number of plus signs and minus signs: (+++++) performance on mulberry leaves (maximum response); (+) a small but definite response; (±) feeding hardly noticeable; (–) no feeding, responses as of starving insects; (– –) survival time shorter than that for starving insects. L, reported in the literature; F, my own experiments (unpublished).

Name of plant	Feeding	Growth	Survival	Reference
		Urticaceae		
Urticaceae	+	?	?	L
Urtica procera	++	–	–	F
		Moraceae		
Morus alba	+++++	+++++	+++++	L, F
Maclura aurantiaca	++++	++++	++++	L, F
Broussonetia kazenoki	++++	++	+	L, F
B. papyrifera	+	–	– –	F
Cudrania triloba	++++	++++	++++	L, F
C. javanensis	+++	+++	+++	L, F
Ficus carica	++	+	– –	L, F
F. elastica	++	+	–	F
F. erecta	±	–	– –	F
F. wightiana	–	–	–	F
F. pumila	++	+	– –	F
F. retusa	+	+	– –	F
F. hirta	++	+	–	F
Humulus lupulus	–	–	–	F
H. japonicus	–	–	–	F
Cannabis sativa	–	–	–	F
Dorstenia contrajerva	–	–	– –	F
		Ulmaceae		
Ulmus sp. (*parvifolia?*)	++++	++	+	F

widely distributed in leaves from various sources and may well serve also to attract other leaf feeders to their food. However, the specificity of the food plants of the silkworm seems to be due to other types of compounds, recognized rather by taste than by their smell, which are typical of the plant family Moraceae. Table 3 summarizes the effect on the feeding, growth, and survival of *Bombyx* of a number of plants of this family (*17*). In this table, five plus signs indicate the effect of the proper food plant *Morus alba,* and the responses of *Bombyx* to other plants are indicated by a series of plus or minus signs. One minus sign indicates that the plant had not been touched at the time of the insect's death, and that death occurred after the same length of time as in an insect kept without food. It may be seen that silkworms feed relatively well on the American tree *Maclura aurantiaca* (Osage orange), on *Broussonetia kazenoki,* and on *Cudrania triloba* and *C. javanensis.* Development of *Bombyx* from the egg to the adult on all these plants has been reported, though growth was slower and the period of survival was shorter than for silkworms that fed on *Morus.* Relatively profuse feeding also occurred on several species of *Ficus,* though for only short periods. Indeed, on a number of the plants eaten, death occurred sooner than it did in insects that had been starving (as indicated by two minus signs in Table 3). This suggests that an attractive principle is widely, if not generally, distributed within plants of the family Moraceae, but that the amount of feeding and the effect on growth and survival are limited by the simultaneous presence of repellent or toxic principles. On the edible fig, for instance, or on the paper tree *Broussonetia papyrifera, Bombyx* feeds eagerly for a few days and then dies. The fact that the larvae feed on Compositae may indicate the absence of a repellent in such plants, but feeding only occurs when the larvae are hungry and is not sustained for long periods From the point of view of phylogenetic distribution of specific plant substances, it is highly revealing that profuse feeding also occurs with the family Ulmaceae, and that similar observations have also been made with respect to members of the Urticaceae. In the natural classification of plants, Ulmaceae, Moraceae, and Urticaceae together form the order Urticales.

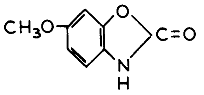
The effect of repellents on the feeding reactions of *Bombyx* is strikingly illustrated by the work of Torii and Morii (*18*). Extirpation of the maxillae resulted in feeding on several plants (for example, cherry and cabbage) which were normally not touched by the insects; obviously this was because they no longer tasted a repellent substance.

None of the attractive or repellent or toxic principles which occur in moraceous plants have so far been identified.

Gramineae

The European corn borer *Pyrausta nubilalis* and the rice stem borer *Chilo suppressalis* are among the few plant-feeding insects which have hitherto been grown on a synthetic diet with some measure of success. However, development was far from optimal in the absence of additional leaf fractions—a fact which strongly points to the importance of attractant substances. The isolation of such a substance from rice plants has now been reported by Munakata *et al.* (*19*). The method of assay consisted of trapping larvae of the rice stem borer in small glass tubes containing the substance. This compound was provisionally identified as an aliphatic unsaturated ketone and named orizanone.

Nothing is yet known about the nature of the attractant for the corn borer. However, evidence of very interesting consequences has been presented about limitation of feeding caused by resistance factors. One fat soluble factor (resistance factor A) which is responsible for the high mortality on young corn plants of pretassel stage has been identified as 6-methoxybenzoxazolinone (*20*) a compound, incidentally, which was also isolated from rye plants and which prevented the growth of the rye plant rot *Fusarium nivale.* Varietal differences in resistance to borers at this stage of growth are positively correlated with varietal differences in concentration of resistance factor A in the plant (*21*). The resistance tends to break down when the plant tassels. The tassel, which is a favorite feeding site, contains little or none of the resistance factor. The occurrence of two other, water-soluble, resistance factors, B and C, has been inferred, but nothing is yet known about their nature.



The oriental migratory locust *Locusta migratoria* has long been regarded as an almost indiscriminate plant feeder. Yet, according to recent investigations by Chin (*22*) (which I can corroborate), in nature it feeds exclusively on about 20 species confined to the families Gramineae and Cyperaceae. In the laboratory, in the absence of grasses, it also grows on cabbage or soybean, but slowly, as a result of diminished feeding. It appears that sensory discriminations serve as the determining factors in selective feeding, but that once the food is ingested, digestion goes on without much regard to difference in food type.

Members of the family Gramineae are characterized by the occurrence of silica in the leaves. It has frequently been assumed that the presence of silica deters animals from feeding on grasses. Isley (*23*) demonstrated that the mandibles of species of grasshoppers which fed on grasses were more highly sclerotized than those of grasshoppers which did not. Sasamoto (*24*), in a series of papers, has shown a correlation between the silica content of rice plants and the degree of attack by the rice stem borer *Chilo suppressalis* Walker. In these studies the silica content of the plants was increased by applying silica to the soil. The leaves of silicated plants caused abrasions on the mandibles of insects which fed upon them.

Conclusion

The examples cited of insects specific to plants of the families Cruciferae, Umbelliferae, Leguminosae, Solanaceae, Moraceae, and Gramineae clearly demonstrate the function of secondary substances in these plants as means of repelling or attracting insects. The fact that, so far, only insects have been discussed does not imply that of all the organisms which depend on plants for nutrition, insects are the only group of importance with respect to the particular phenomenon under discussion. In fact, the first comprehensive statement on this topic, by Stahl (*25*), originated from a consideration of the relation between insects and snails, and there is every reason to assume that other organisms, such as mites and, in particular, the vast array of pathogenic and commensal microorganisms, from bacteria to fungi, which inhabit plants, are affected in a similar way by secondary plant substances. Insects, however, not only provide at present the best known instances but also in all probability are, of all organisms, the ones that play the principal causative role in this relationship.

This relationship between secondary plant substances and insects does not come as a surprise to the entomologist and ethologist, who have always been impressed by the power of discrimination of the chemically stimulated senses of insects, not only in the areas under discussion here but also in the reactions of insects to animal hosts of all kinds, in the mutual recognition of the sexes, and in the selection of egg laying sites. But it must come as a surprise to the plant physiologists, biochemists, and organic chemists, who for generations have been dealing with these substances and who have been entirely in the dark about the proper function of these compounds for the plant—indeed, about their *raison d'être*. In the innumerable books and papers which have been written on glucosides, tannins, alkaloids, and essential oils, one searches in vain for a comprehensible and comprehensive statement about the true function of these compounds and their origins in the phylogeny of plants, And yet, the views here expressed were stated over 70 years ago with great forcefulness by the German botanist Stahl (*25*) in a treatise on the protection of plants against snails. They were first successfully put to the test by Verschaeffelt (*3*) in his already cited investigation on *Pieris* butterflies and Cruciferae and subsequently restated in various perspectives by Dethier (*26*) and by me (*27*). There were full discussions of the insect–host-plant relationship in two symposia held in recent years—that on the "Physiological Relations between Insects and their Hostplants," at the International Congress of Entomology, held in Amsterdam in August 1951 (*28*), and that on "Insect and Foodplant," held in Wageningen, the Netherlands, in 1957 (*29*).

To summarize, it would be difficult to find a more lucid and concise statement than the following sentences, which close Stahl's pioneering article (*25, 30*):

"We have long been accustomed to comprehend many manifestations of the morphology [of plants], of vegetative as well as reproductive organs, as being due to the relations between plants and animals, and nobody, in our special case here, will doubt that the external mechanical means of protection of plants were acquired in their struggle [for existence] with the animal world. The great diversity in mechanical protection does not appear to us incomprehensible, but is fully as understandable as the diversity in the formation of flowers. In the same sense, the great differences in the nature of chemical products [*Exkrete*], and consequently of metabolic processes, are brought nearer to our understanding, if we regard these compounds as means of protection, acquired in the struggle with the animal world. Thus, the animal world which surrounds the plants deeply influenced not only their morphology, but also their chemistry."

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30. Translation from the German by G. Fraenkel.

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