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Title Page

Toward a theoretical explanation of electro-chemical interaction in memory use: The postulated role of infra-red components and molecular evolution

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Apart from the new "Forward", there are no substantial further changes in this 2006 online republication.
Minor text changes from the 1980 version are indicated in dark blue. Post-publication proof-read corrections: March 2006.
Pages have here been reformatted and renumbered, and some diagram captions have been reorganized.

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Toward a theoretical explanation of electro-chemical interaction in memory use: The postulated role of infra-red components and molecular evolution

Robert R. Traill

FORWARD — ONLINE EDITION 2006

What realistic bio-mechanisms could possibly explain advanced human mental abilities, and do this explaining in some depth without the usual vagueness?

In the 1970s, that investigative project was launched via three interrelated works. This "Monograph 24" (1977) was the most technical of the three, venturing into the likely underlying *Physics* and *Information-Technology.* (At a more informal level, it finally considers possible evolutionary implications and the role that glial cells might play. See chapters 5 and 6 below.)

The other related works (published in *Kybernetes*) dealt with issues more closely related to philosophy and Piagetian psychology— questions perhaps lying closer to the typical Arts faculty than to classical Science. To be more specific:

1. *(Traill, 1976a — part I). "Acquisition of Knowledge…".* This dealt with the in-principle dilemmas of epistemology as raised by Popper in his later works, and sought to marry these ideas with Piagetian concepts and with how these might be implemented biologically. Linear strings-or-tapes of coding were here seen as the most likely embodiment for Piaget's "scheme" elements — a possibility which Piaget himself occasionally implied. On that basis, these "tapes" may be seen as capable of "communicational" (virtual) assembly into more stable mental constructs — thus forming coherent collective systems by a process which Piaget called "equilibration".
This theme has since been developed in further detail, mainly Traill (1978a, b; 1999 chap.4; 2000 chap.7; and especially 2005b).

2. *(Traill, 1976a — part II).* This seeks to apply the same approach to *science-as-a-whole* in its search for coherent theories — epistemology as a *social* enterprise (rather than an individual's task). It is concluded that any search for certain-truth is misguided; but that we can-and-do often make good approximations to this ideal, and we would be wise to be content with that.
This was later discussed in Traill (1999; 2000 espec.chap.2; 2005c). Also see Thagard (1992, 2006).

3. *(Traill, 1978a). "Analytical Theory of Sensori-Motor Spatial Development".* As already noted, this goes further into the issues raised in item 1 above. In particular it seriously considers RNA as a candidate for the role of "string-or-tapes" of coded information deemed necessary for a Piagetian system. In this it considers practical complications which might arise, and how they might implement details of Piaget's conceptualization. — See "1" above for further references.

Returning now to the present work, the key issues are:

Chapter 1: Efficient communication between molecular sites — Infra-Red or what?
Action-potential "spikes" clearly play a vital role in neurophysiology, but that does not necessarily mean that they have a complete monopoly over the body's "telecom" systems. If indeed molecular coding-sites are indispensible to some aspects of mental activity, then it is difficult to

see how they could intercommunicate efficiently using only the textbook action-potentials (of about *1 msec* duration) at any time when finesse was required. Instead we could plausibly expect emission-and-absorption via the *Infra-Red quantum jumps* natural to organic metabolism — provided that this was otherwise realistic within the bio-environment. But note the vast quantitative difference with wave-periods now a mere 10^{-15} *sec*. or so — and that suggests the possibility for a "new beginning" with new prospects, but it might also stretch one's credulity!

This issue was later raised again in Traill (1988) — a paper which, in some ways, served as a précis of the present 1977 work — and also in Traill (2000, Part II).

Chapter 2: Storage and retrieval of memory (now assumed to be molecular).

In retrospect one can see that this is essentially the same as the dilemma which faced Darwin over the adaptation of species to their environment. Here, instead, we have *the physical encodings of ideas* becoming adapted to *their* environment — and the solution might plausibly be essentially the same: trial-and-error (plus considerable "waste"), with *no Lamarckian direct-storage* at all! — See later discussion, mainly in Traill (1999, chap.4).

Back in 1977 though, I first saw this instead as simply implicit within the Piagetian system of *action-first, followed by learning*. Again it is the same idea, and no doubt Piaget's concept was at least partly prompted directly by Darwin.

Chapter 3: The surprise finding that myelin could double as optic fibre for Infra-Red.

In the mid 1970s, I was studying the theory of saltatory conduction (the way a millisecond action-potential "spike" leaps along a myelin-insulated segment of a nerve-fibre). It then seemed obvious to me, as a physicist, that such structures were essentially coaxial cables, and that the text-book formula was ignoring the inductance "L". Now it just so happens that correcting this omission goes some way to explaining how such coaxial segments can *serve two separate signal-carrying roles simultaneously*: (i) the textbook account of millisecond "spikes" between synaptic sites; *AND* (ii) the vastly different (postulated) Infra-Red transmissions between molecules linked by individual myelin segments (typically *1 or 2 mm* in length). Meanwhile there was a huge hiatus of intervening frequencies for which such signalling was evidently impossible — and this had helped to hide the second possibility "on the other side of a wide ocean".

This chapter 3 insight seems to have been new to neurophysiology — in fact it is still virtually unknown there — but it turned out that this was actually an old 1880s battleground in the context of trans-Atlantic cables. Meanwhile neurophysiologists are still using Kelvin's 1860s' equation!

Later works on this "fibre-optic" issue are Traill (1988, and 2000 part II) — and there have been windfall extensions of the concept which offer explanations to long-running mysteries about the micro-morphology of cells and myelination (Traill 1999, chaps 6-7; 2005a).

In general: One may, or may not, find these accounts persuasive individually. But if one considers them together collectively, they do seem to offer a coherent picture and hence a possible way forward to better insight about mental processes, and perhaps other metabolic activity as well. It might thus be interesting to see how this ensemble of concepts measured up if one applied Thagard's ECHO test-of-explanatory-coherence (Thagard 1992, 2006). However it would be best if I were *not* the one to administer any such test, so I invite others to do so.

Finally, a pedagogical note about the somewhat "mystical" concepts of chapter 3, (see above):

The more recent accounts of myelin's postulated double-role are more sophisticated, applying Maxwellian concepts and hence turning the exposition into an *optics* discussion — fibre optics in fact. That is fine for some students-or-readers, but others may be more attuned to the traditional circuit theory of "R, C, L, and current I" etc. In that case, the present account may be more useful because that indeed was my own approach at the time I started writing it. (This will probably be obvious, especially given the apparent need to add further clarification later — as the 1980 notes explaining the limitations of the "L" equation which is now on page 6.)

In that case it might be helpful to explore the following progression of ideas, though I do not necessarily recommend it: (i) Naively accept the L and C equations as written on page 6, and explore the consequences as the frequency rises (*viz.* failing performance due to increasing capacitive leakage, and negligible inductive effects until frequencies are very high, but then able to match the capacitive effect — and then (seemingly!) surpass it, implying an "X" graph).

(ii) Correct this, by now taking into account the 1980 notes about changing field distribution — see page 6 — and also section 3.2 (page 20, associated with footnote 5). In this case one can convert the graph to a "≻" approximately — signifying an eventual mutual-cancellation balance between the two reactive impedances (ωL and $1/\omega C$) at the highest frequencies.

However, at that stage one may begin to see the merit of an optics treatment instead! After all, fibre optics is hardly a novel concept by now.

R. R. Traill, 27 February 2006

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ORIGINAL ABSTRACT

This is the third in a series of works which collectively set out to offer overall unity and structure to the concepts of psychology and neurophysiology.

The present paper is concerned with technical questions of how the previously-postulated formal mechanisms (Traill, 1976a) could actually exist and operate effectively within the known neurochemical and neurophysiological environment.

The key problem concerns the detailed mechanism whereby chemical memory-storage could be effectively "read out" onto effective action, and just how it could have come to be "written down" in chemical form in the first place. Communication with such stores seems best explained in terms of emission and absorption of infra-red signals; and problems of re-coding may be explained in terms of high dispersion and interference within "distortion-prone" optical paths. Meanwhile problems of "writing down" (and problems of teleology) may be explained by a radical postulate of encoding by trial-and-error at the molecular level.

Evidence for these notions is mostly indirect, but there is an encouraging degree of corroboration from apparently-unrelated sources.

BASIC ELECTROMAGNETIC SYMBOLS AND CO-AXIAL FORMULAE

E [*volt/m*] is the electric intensity field vector.

H [*amp/m*] is the magnetic intensity field vector.

ε [*Farad/m*] is the permittivity of the medium;
(8.85×10^{-12} *Fd/m* in vacuo: "ε_0").

μ [*henry/m*] is the magnetic permeability of the medium;
($4\pi \times 10^{-7}$ *henry/m* for non-magnetic media: "μ_0").

ω [*radians/sec*] = $2\pi f$

f [*Hz = cycles/sec*] is the frequency.

λ [*metres*] is the wavelength, either in vacuo (λ_{vac}) or in the specified medium (λ_{med}).

C [*Farad*] is the capacitance; and in the case of co-axial cable we may express this by the Thomson's (1855a) formula (expressed in modern SI units):

$$C = \frac{2\pi\varepsilon \,.\, s}{\ln(r_2/r_1)}$$

(where *s metres* is the length).

L [*henry*] is the magnetic self-induction; given, for coaxial cable, by the analogous formula:

$$L = \frac{\mu_0 . s}{2\pi} \,.\, \ln(r_2/r_1)$$

Comment added July 1980:- As it stands, this last formula assumes zero magnetic penetration into the conductors. It therefore begins to break down as the inductive impedance approaches the capacitative impedance. This does not materially affect the present argument which depends on these two opposing reactive impedances becoming effectively equal at about the frequency stated in section 3.2. However it does mean that this equality will continue indefinitely as the frequency rises further — as befits optic effects. (Morton, 1966).

Chapter 1

1. Introduction: the search for a rigorous structural theory of memory

SUMMARY OF CHAPTER

This chapter poses some basic questions about how behavioural psychology could possibly be rigorously explained in terms of realistic biological mechanisms — in particular questions about selective communication with different chemical memory-stores.

As long as we insist that physiological action-potential is the basic indivisible unit of such communication, then any rigorous explanation proves to be disturbingly elusive. However there turn out to be some persuasively corroborative arguments that there may be an important and rich fine-structure to these and other neural phenomena — involving frequencies above 10^{11} *Hz* — and this would make the explanatory task much more feasible.

During the decade up to 1977, a number of workers evolved theoretically or experimentally inspired suggestions concerning micro-wave or infra-red electromagnetic effects as accompanying: neural activity (Fraser and Frey, 1968; Agrawal, Singh, and Gupta,1977); cell-division (Moens, 1973); the activity of mitochondria (Cope, 1973); biological processes in general (Fröhlich, 1968, 1975; Kollias and Melander, 1976; Bhaumik, Bhaumik, and Dutta-Roy, 1976; Webb and Stoneham, 1977); or chemical correlates of learning (Ansell and Bradley, eds, 1973; Glassman and Wilson, 1969). It would appear that all such studies have hitherto taken their main initial inspiration within the comparatively "hard" sciences of biophysics or biochemistry.

By contrast, my own interest in the field springs from problems within the behavioural and psychological sciences; especially the methodological impasse posed by the sheer impossibility of collecting anything like an adequate experimental description of the state of a dynamically functioning intelligent and sentient being. To break this impasse, the attempt has been made to use a different approach — regarding the investigatory task as something resembling an engineering-*design* task, with observed macro-behaviour as the design-*goal*, and the established findings of physics, biophysics, physiology, and biochemistry to represent the "*specifications of materials*".

The interesting thing is that theorizing along these lines led, in the first place, to a plausible design in which it was supposed that somewhere there existed linearly-constructed material strings of coded information, and that these should exist in intercommunicating *populations* (Traill 1976a, 1978a). As we shall see below and elsewhere, there is also considerable explanatory potential to be gained from postulating that these linear elements are extremely small and multitudinous — allowing ample scope for redundancy and Darwinian trial-and-error procedures amongst mental constructs, without being unacceptably wasteful of resources. These theoretical considerations clearly point to the likely involvement of linear macromolecules in mental activity — quite independently of experiments implicating specific types of macro-molecule.

The trouble is that no adequate structural theory can rest there. If such molecules are to be taken as repositories of coded information, it is necessary to explain at least three things: firstly, how they could feasibly intercommunicate with each other and with the sensory and effector organs of the animal; secondly, how such signals could be selective and meaningful; and thirdly, details of how such codings could be controlled and manipulated to produce the astonishing behavioural repertoire which is exhibited by animals, especially man. This present discussion will deal with the first two questions (on intercommunication and its selective properties), while the third (behavioural) issue is dealt with in Traill (1978b, Part C) and in subsequent publications.

Concerning the intercommunication issue:- In retrospect it can now be seen that there are actually two or three current schools of though about the nature of fundamental peri-neural communication, and that at first sight these might be supposed to be mutually exclusive alternatives. There is the comparatively new notion of sub-centimetre electromagnetic radiation alluded to above and associated with the disciplines of biophysics and biochemistry, (and as we shall see, we may subdivide this into roughly *millimetre* and *micron* bands respectively). But there is also the much older-established physiological concept of the action-potential "spike" which has so far dominated the theorizing of those psychologists and brain-modellers who chose to speculate on the fundamental structural bases of behaviour.

One serious trouble with this latter physiological approach is that it is very difficult to envisage any feasible mechanism whereby the *chemical* memory storage (Ansell and Bradley, eds, 1973; Glassman and Wilson, 1969) could effectively intercommunicate sufficient information with the *electrical* action-potential patterns — each spike being of roughly one millisecond duration, and so having spatial pulse-lengths very much greater than any feasible chemical storage structure, given any realistic propagation velocity (Goldstein and Rall, 1974).

Within the present project, this difficulty led to a closer investigation of the physics assumed by the physiological account of such phenomena, especially the theory of "electrotonic" explanation for saltatory conduction of action-potentials across myelinated segments of nerve fibre — an explanation for which there seemed to be no rigorous formulation. The result, discussed below in chapter 3, partly vindicated the physiologists, but it *also* pointed to *another solution* which indicated that infra-red frequencies could be actively involved in the process of saltatory conduction — using *optical* rather than *circuit-theory* principles; (a point which, it turns out, was argued by Heaviside a century ago in connection with submarine cables).

There have in fact been several attempts from within the psychological and neuro-physiological disciplines to suggest causal connections between the traditional action-potential phenomena themselves and the supposed structural representations of Long Term Memory; but the chain of explanation always seemed to have a weak link at the interface between electrical and chemical phenomena.

Holograph and correlograph theories (reviewed by Pribram, 1971) are a case in point. For instance, Pribram's (1971, page 43) postulated mechanism of "induced" mitotic division does not, as it stands, include any detailed suggestion as to how electrical spike-or-wave interaction phenomena might trigger the postulated mitosis. Similarly the neurophysiological account of how "transmitter substances" come to be released electrically from their vesicles during exocytosis, (Katz, 1966; Pysh and Wiley, 1974; etc.), has seldom if ever faced up to the problem of just what mechanism might be capable of causing such a release.

There are further difficulties too. If we accept no communicational encoding other than that provided by millisecond "spikes" and possibly other phenomena in the audiofrequency range, then it is difficult to see how a sufficiently stable oscillator system could be provided (Willshaw, Longuet-Higgins, and Buneman, 1970) so that the holograph principle loses its credibility. We then seem to be left with little more than Hodgkin-Huxley thresholds to be triggered by the quasi-static audiofrequency voltage changes — which do go some way toward explaining chain-reaction propagation, but give little guidance on sophisticated concepts like memory-storage and selectivity.

Thus, even if we go no further than the arguments most relevant to reductionist *psychology*, there are still several grounds for dissatisfaction with the pure uncomplicated action-potential model used normally for such explanations in this field. Moreover in retrospect it can be seen that any one of these "antinomies" might lead one to postulate a solution in the form of optical components within the apparently-pure action-potential. In this case the clue actually came from (i) the mathematical investigation of myelinated nerve fibres, but it could also have arisen as an explanation for the other problems: (ii) practical holography, as Pribram has been inclined to concede (personal communication, 1976) — also pointing out that this would fit in with existing notions relating to the chemical senses (Beck and Miles, 1947; Pfaffman, 1951); (iii) the triggering or driving of intra-cell dynamics in response to specific signals (Lee and Chaing, 1976; Hodson and Wei, 1976); and (iv) the high information-carrying capacity which would seem to be required to account for the actual behavioural repertoires of adult mammals.

Having once suspected the involvement of infra-red components, on any of these psychologically-oriented grounds, it does not require much insight to realize the "hard-science" fact that any chemical storage of information in a biological system is likely to be intimately involved with emission and sbsorption spectral bands within the infra-red range (whether or not these will be detectable as macro effects). And looking a little further, it seems likely that any physical movement of relevant molecules is likely to be associated with another range of radiation having wavelengths in the millimeter range (short Microwaves). This latter model was developed in some detail, mainly in connection with the problems of cell dynamics related to meiosis (Moens, 1973), though it might well have applications relating to the physical organization of basic elements of memory (see Traill (1978b); especially chapter C8). The present account will, however, concentrate on matters relating to infra-red rather than the supposed molecule-*shifting* activities of microwave frequencies.

It may be said that there is by now a strong case to support the view that infra-red *is* involved in neural activity *somehow*; but very little has so far been said about its potential for information-encoding and transmission — questions of prime importance to the understanding of meaningful behaviour and learning. In particular we need to ask how chemical encodings might be "read off" into practical action or thought — and how, in the first place, meaningful codings could have come to be "written down" as internal records of experience. These are problems fundamental to a proper understanding of biological memory, and the present work will be particularly concerned with theoretical solutions to these questions.

Although the chronological development of the present study would suggest starting with the analysis of saltatory conduction as outlined above, it seems more appropriate to start instead with the chemical-storage issues. These will be more generally familiar and more obviously relevant to the present issue of memory mechanisms; while, to start with, the arguments relating to saltation will simply appear to be secondary corroborative evidence — albeit important evidence.

Chapter 2

2. How could bio-electrical messages be converted into meaningful and specific chemical coding — and be retrieved ?

SUMMARY OF CHAPTER

It can now scarcely be doubted that mental activity involves both electrical communication and chemical storage. The prime question then is, what connection could there be between these two types of phenomenon? This leads to an evaluation of the role that infra-red and sub-picocecond events might play in providing such a link.

However we also need to be able to offer biologically feasible mechanisms for both the initial encoding of memories and their subsequent selective retrieval. Thus suggestions are offered to explain selective triggering of particular chemical stores, and the consequences which are likely to follow — as motor action or further internal triggering. But the most enigmatic feature of all is the laying down of memory in the first place; and here it seems necessary to postulate a system of trial-and-error at molecular level, so that the encodings of both action and perception can be judged by their results — in line with Piagetian concepts of mental development at the behavioural level.

2.1 a special role for infra-red?

If neural signals and chemical memory are to interact *selectively*, then clearly there must be some sort of *match* between the chemical and the elecrical sides of the transaction. Presumably the electrical matching ultimately takes the form of assessing a wave frequency or *pattern* of frequencies, in conjunction with DC and quasi-static effects; and such wave phenomena are most likely to be of an *electro-magnetic* nature. (Relatively crude sound-like intermolecular propagation might also be involved, though this will not be considered in any depth here; see Lundström (1974)). For frequencies to match at the molecular level, as required for chemical effects, any signal-capture mechanism will almost certainly involve the molecular resonance frequencies or absorption bands — though possibly in a more subtle and complex manner than one usually associates with such phenomena. Thus we would be rash to assume that a *simple* continuous radio-like frequency is all that is required to give the necessary specificity.

As it happens, the likely frequencies for chemical absorption turn out to be in roughly the infra-red range — very much higher than one would expect from attempting a fourier analysis of the electrical phenomena as observed in connection with physiological action-potentials (reviewed by Eccles (1964), and by Katz (1966)). The observable components of action-potentials are mostly in the audio-frequency range (roughly 1000 Hz), while infra-red involves frequencies of the order of 10^{14} to 10^{11} Hz — from the near-visible down into micro-wave frequencies, respectively.

At first sight then, these infra-red frequencies seem to have almost nothing in common with the audio-frequencies of the action-potential, and the two bands appear to constitute the basis for two mutually exclusive theories. In fact though, there *is* a qualitative connection, however tenuous. Moreover there seems to be no compelling *a priori* reason why they should not either co-exist independently within the same medium (and such multiplexing is commonplace in signals engineering); or else both could be manifestations of the same basic phenomenon — but manifestations which could not readily be displayed by the same measuring apparatus.

Furthermore other frequency bands might also operate within the same medium under favourable circumstances; though these would be likely to have different biological functions and transmission properties. For instance there is evidence from the USSR, cited by Fröhlich (1975), of “a striking influence of *6-7 mm* coherent electromagnetic radiation”. Other work has investigated this matter further, and it seems that such frequencies may play an important role in the dynamics of complete macromolecules (Moens, 1973; Holland, 1972).

One aspect of the view concerning infra-red has been developed in considerable detail, giving a convincing theoretical explanation of observed phenomena relating to Hodgkin-Huxley propagation along unmyelinated nerve-fibre membrane (Lee and Chiang, 1976; Hodson and Wei, 1976). This view also finds some direct *experimental* support in the work of Fraser and Frey (1968) who detected infra-red radiation (band-pass of 2µm to ≥20µm) escaping from near the nerve surface when it was activated.

It is interesting to note the implication that there may be a clandestine use of infra-red components in the unelaborated operation of Hodgkin-Huxley propagation — where this includes restoration of the equilibrium "dipole system" (Lee and Chiang, 1976). And here we are not even invoking the four "antinomies" mentioned above in chapter 1 (saltation, holography, intra-cell dynamics, and the information capacity in higher animals). The likely existence of such phenomena, operating on a basis of partially random quantum events, makes it more credible to postulate a similar quantum basis for at least some of the four antinomies — especially if we now consider the possibility that the supposed randomness of the quantum effects might be superceded by something more controlled, synchronized, and systematic — instead of being primarily dependant on the laws of statistics.

But there is yet a further independant line of theoretical corroboration for the notion of the importance of infra-red in neural activity and elsewhere. Cope (1973) points out that the metabolism of ATP involves *±9 Kcal/mole*, which is *0.39 eV/molecule*, and accordingly produces a phonon-quantum of wavelength *3.24 µm.* We might also expect comparable-but-longer wavelengths when some energy is used up on overcoming potential barriers, or suchlike. (He also then goes on to explain quantitatively how such a wave-particle might reasonably be stored as a *standing* wave in a mitochondrion membrane, or form a *travelling* wave in other bilipid membranes. We will return to such concepts in chapter 3).

2.2 Specific patterns of sub-picosecond events as triggering stimuli

If we tentatively accept the relevance of infra-red frequencies for signal transmission and storage, then the following frequency bands seem to be amongst those most worth considering, (see Table 2.2/I).

TABLE 2.2/I

Absorption-bands likely to be relevant to chemical signal storage and retrieval in the brain. Terms like "wagging" are explained in Szymanski (1964, section 4.3).

wavelength (in vacuo) µm	corresponding frequencies 10^{13} Hz	Description	Source
20	1.5	(weak), chain-deformation	Hummel, Holland-Moritz, and Zoschke (1972)
10 - 13.8	3 - 2.2	stretching in ester groups, or rocking in methylene groups	
7.15 - 8.33	4.2 - 3 6	wagging in methylene groups	
6.7 - 7.15	4.5 - 4.2	bending in methylene groups	
5.78	5.2	carbonyl groups	
3.4 - 3.5	8.8 - 8.55	stretching in methylene groups	
2.6 - 3.6	11.5 - 8.3	CH, NH, and OH stretching	Kaye (1954)
1.7 - 2.5	17.5 - 12	combination bands	

Also Thomas, Austin, and Davies (1954) had examined nervous tissue and suspected that five bands in the *5 to 15 μm* range were particularly important: *5.7 μm*, *6.8 μm* , *7.1 μm, 7.2 μm*, and *13.9 μm*. These could plausibly be identified with bands listed in the table. But even granted that such frequencies are functionally involved in "reading" or "writing" the chemical encodings of experience-based information, this would still leave a number of difficulties which we will need to examine. To start with, it should be remembered that there will be a very considerable random noise-level in this infra-red range. Thermally produced radiation at body temperature would be expected to peak at wavelengths of about *9 μm* and spread appreciably on either side of this. So if infra-red frequencies are to be used at all for signal transmission, some highly specific coding system would seem to be essential.

> [On the other hand, this potential abundance of random radiation does make it conceivable that some sort of mechanism, perhaps operated by other frequencies, might "gate" infra-red cues onto molecular sites. This might perhaps be the basis for an alternative theory or a refinement of the present one, but we will not discuss it further here.
>
> Rather more to the point though, we shall see below that water absorption is likely to drastically eliminate any ambient random signals which are not under specific control and "protection". In fact, at first sight, this formidable magnitude of absorption (Robertson, Curnutte, and Williams, 1973; Ray, 1972) seems to pose another serious problem for any theory involving infra-red transmission. These issues will be discussed below in section 3.4].

Moreover such signal specificity — the term being used here to signify *non-randomness* — would seem to be essential anyhow; that is if chemical memory is to be accessed by "label" and not merely by location. One obvious but trivial way of accessing a specific label would be to use a matching resonant frequency, though it is difficult to see how a single-frequency coding would provide an adequate variety of labels. Instead it would be reasonable to expect a label-code to consist of a spatial or time-sequential *pattern* of code elements, such as an ordered sequence of frequencies within the neural system, similar to a spoken sentence travelling acoustically through the air. But it remains for us to explain just how such a pattern might be reliably processed and then reliably acted upon or stored.

2.3 Emission and reception of selective signals within the infra-red range.

We shall mainly be concerned with signal-*reception*, leading up to section 2.4 and the enigma of the "writing down" of experience-based encodings into chemical storage, but let us look briefly at signal *emission* first. This might occur as an emitted ordered-sequence of frequency codes produced by an RNA-like physical sequence, having consecutive sites which "fire" in an ordered chain-reaction, thus producing some sort of modulated stream of waves or pulses. Alternatively (or concurrently) the emission might take the basic form of a "click" or isolated standard-shaped pulse, caused perhaps by a single sodium ion bursting through a cell-membrane pore, in some standardized way or synchronized conformational changes at specific macromolecular sites (Fig. 2.3/1). Any such pulse might well form a collective pattern with other similar pulses (quite likely triggered after a predictable delay), thereby producing a standard population-cluster or "envelope" of pulses, actually distributed somewhat in space and time, and therefore having properties of both the envelope and the individual pulses (with their main fourier components possibly in the infra-red range[1]). Moreover if such pulse signals pass through an

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[1] When stated thus, in terms of fourier components, this assumes a classical rather than a quantum physical basis. It will suffice here to justify this statistically by postulating a sufficiently synchronized *volley* of pulses (or wave-packets) — in close proximity — such that they would have a characteristic *collective* wave form (or pulse-shape) under these circumstances.

optically dispersive medium, such as a Newtonian prism or a “distorting” waveguide, then any reliably shaped pulse will spread its fourier components into a characteristically distributed pattern (in space and/or in time) which might then be detectable by virtue of this distribution. For instance, one component might prime a reception-site to deal with the other components when they arrive after the ‘correct’ delay.

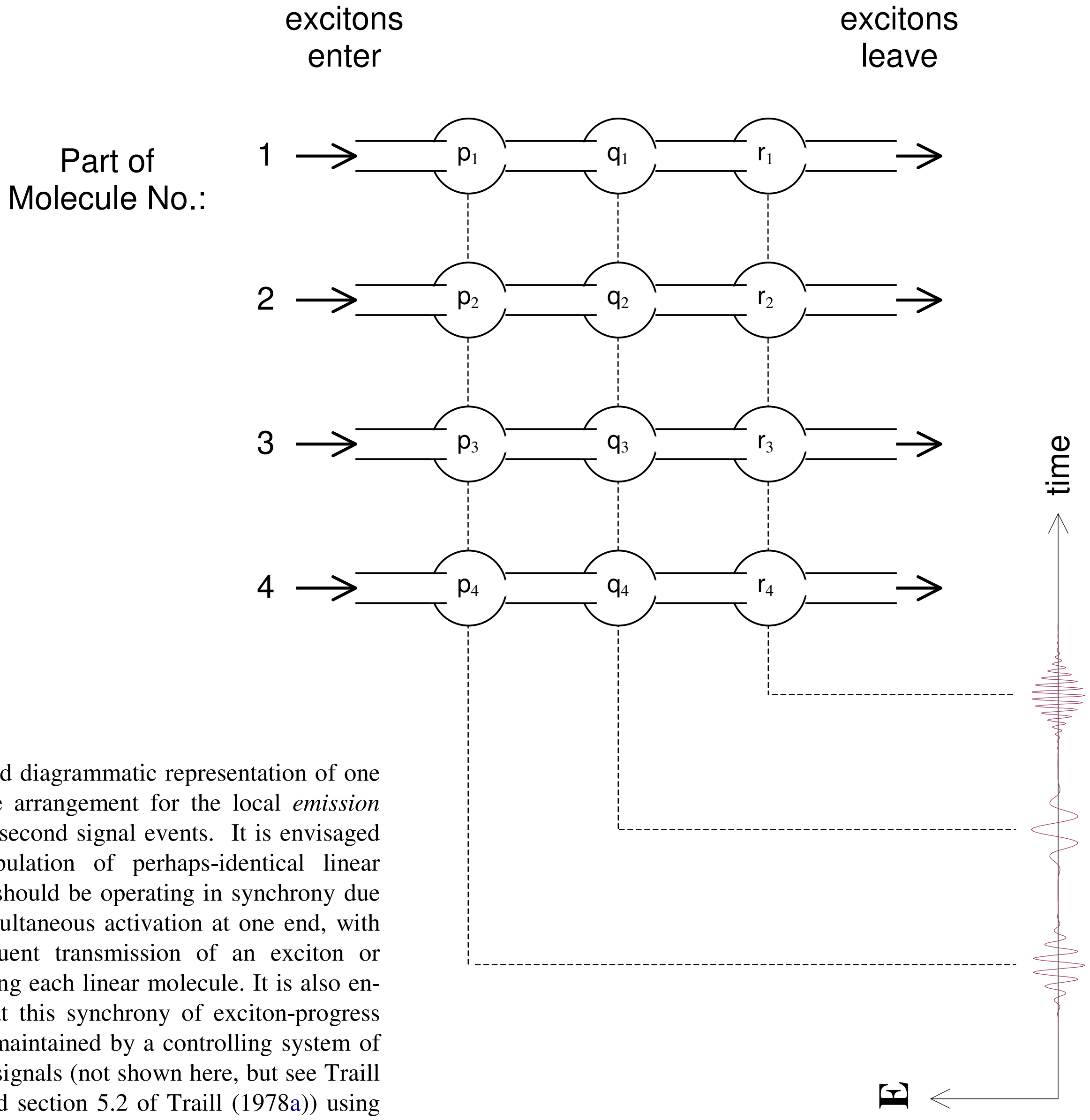

Fig 2.3/1

An idealized diagrammatic representation of one conceivable arrangement for the local *emission* of sub-picosecond signal events. It is envisaged that a population of perhaps-identical linear sequences should be operating in synchrony due to near-simultaneous activation at one end, with the subsequent transmission of an exciton or phonon along each linear molecule. It is also envisaged that this synchrony of exciton-progress should be maintained by a controlling system of cross-feed signals (not shown here, but see Traill (1976d) and section 5.2 of Traill (1978a)) using the control principle of “Model IV” in Monod and Jacob (1961).

> (The non-linear responses observed by Ressler (1976) seem to be consistent with population-interaction effects similar to those envisaged here.)

The graph suggests broadly the type of resulting fluctuation there might be to *one* component of the electric field vector (**E**) at some point — perhaps after some reactive modification has already been effected by transmission through a material medium.

It has been argued (Traill 1976a, 1976e)[2] that all action and sensory schemata, and indeed all ‘engrams’, are ultimately coded in terms of linear-sequence elements. These elements are envisaged as being “RNA-like”, and their new codings were seen as initially forming by “genetic-crossovers” between them and other elements activated at about the same time, (or possibly by other genetic-like “mutations”). These new elements were likely to be dissolved subsequently if they were non-adaptive. The importance of *linearity* in such theorizing is its adaptability; but it would also be reasonable to suppose that for activities like Hodgkin-Huxley propagation, where adaptability is presumably not required, an orderly two-dimensional matrix of sites would seem to be acceptable or preferable. Whether or not Hodgkin-Huxley propagation actually does involve such considerations is open to question, and it is not vitally relevant to the present discussion; but it might be argued that the orderly arrangement of apparent pores through nerve-fibre membranes (Livingston, Pfenninger, Moor, and Akert, 1973) is consistent with such a view. Also such considerations might conceivably shed additional light on how action-potentials sometimes propagate into one axonal branch, but not another (Waxman, 1972; Grossman, Spira, and Parnas, 1973).

We shall turn now to the more straightforward aspects of signal *reception*, namely those cases where the signal merely *activates* structures which have already been set up into some sort of coded “program”. As our present concern is with adaptable systems, we shall confine our attention to how this reception might be performed by *linear* RNA-like sequences which are structurally similar to those postulated for emission. The question then is how, on the whole, a given signal or “call” could be selectively received at the “correct” RNA-like element, or ensemble of such elements. (And in this, it is well to bear in mind that, if waveguide dispersion or other optical interference phenomena are operating effectively, then the signal received may have a shape which bears little resemblance to the pulse-or-wave shapes emitted initially — though ultimately we might well be able to trace the course of such a transformation which would virtually amount to a translation into a new code).

One very primitive approach to the problem of selective reception would be for each different type of receptor to have its own single characteristic absorption band. But to obtain a more credible range of distinguishable call-signs we must expect the receptor to be much more discriminating regarding the exact formation of an extended signal-sequence. This might, for instance, consist of *n* successive photons (at appropriately spaced intervals of time) with the right permutations of frequencies, polarization orientations, spatial distributions, and perhaps phase-relationships — all within sufficiently close tolerances.

This sort of sequence could plausibly be selectively detected using one or both of the following two techniques, and possibly others as well. Consider a particular excitable site along a linear molecule — such as “*A*” in *Fig 2.3/2* — and imagine that only under very specific circumstances will it be possible to excite this site into state A^* and then state A^{**}, and thence to state A^{***} (by which stage we will suppose that the signal *has* been fully “received”). These three transitions might, for instance, only be effected by three different specific signals which would, respectively: (i) Induce a stretching vibration in side-chain *X*, then (ii) induce an accurately synchronized bending in side-chain *Y*, and then (iii) a well-timed wagging of *Y* in plane so-and-so. Such an orchestration of specific excitation would then presumably “catalyse” some otherwise improbable transaction — which could arguably take the form of passing on an exciton (or electron, or whatever) to the next site along the linear molecule, and so perhaps leading directly or indirectly to a new set of emissions.

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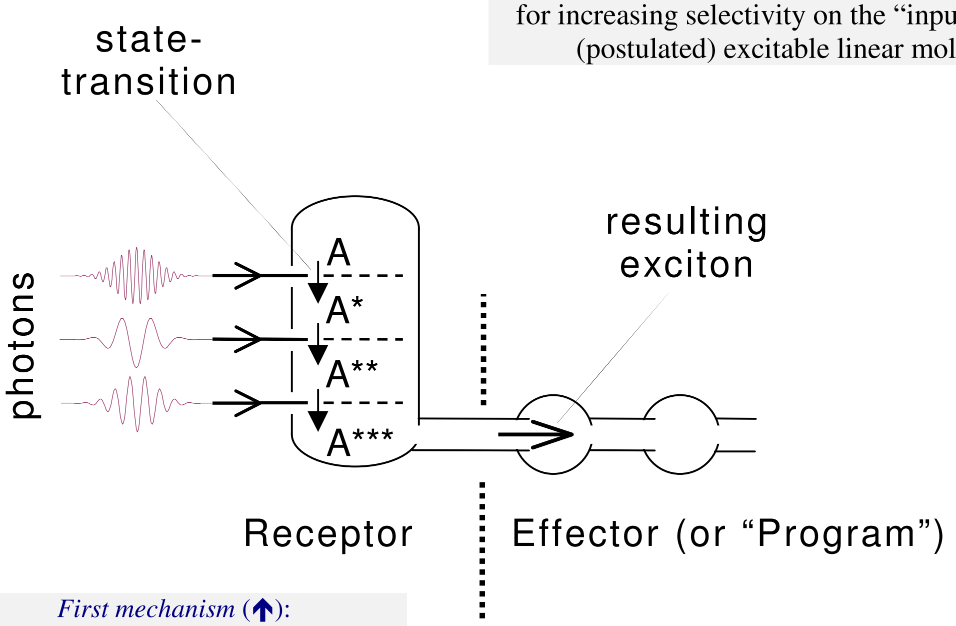
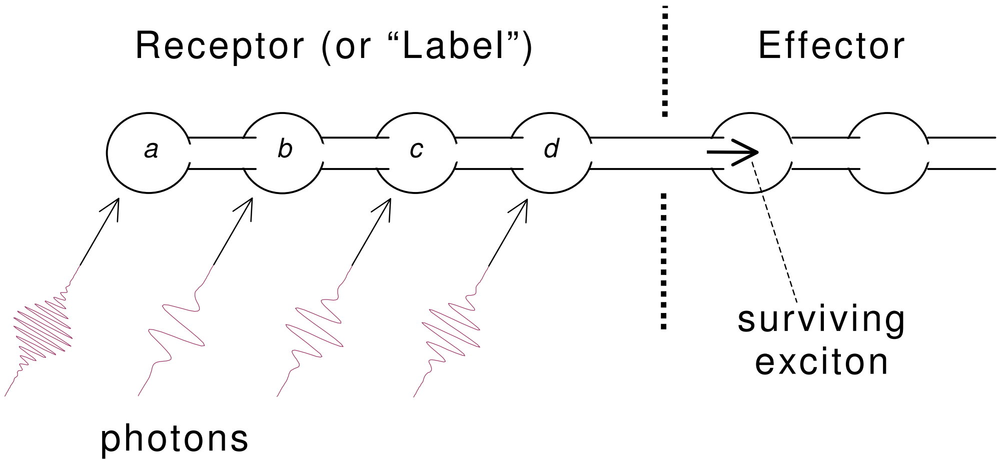
[2] also subsequently in Traill (1978a and 2005b) — [RRT, 2006]

Fig 2.3/2 Two potentially compatible mechanisms for increasing selectivity on the "input" side of a (postulated) excitable linear molecule.



First mechanism (↑):
State *A* may be built up to state *A**** (say) if a "correctly" patterned stimulus is applied. This will make possible the activation of the molecule's own program-code, such as the "*p-q-r*" depicted in Fig 2.3/1 above.
The receptor would then presumably revert back to state *A*.

Second mechanism:
The "b, c, and d" sites are seen as depending on the correctly synchronized arrival of appropriate photons, as well as depending on the internal exciton-signal.
↓



In this second case at least, the need for synchrony and other precise timing could amount to "and-gates", comparable to those of "formal neuron" theory (Blum, 1962).
The logic-element possibilities of such sites are developed further in Traill (1978, section C6.5).

Alternatively, site *a* might readily be induced to pass the internal exciton along the molecule — requiring perhaps only one simple "correct-frequency" photon (also satisfying other easily-fulfilled requirements such as location and polarization); but then site *b* would depend for its activation on *both* the exciton from *a* and *also* an appropriate photon of its own, appropriately timed. Then the selectivity could be made still more demanding by imposing further requirements of a similar nature at sites *c*, *d*, … and so on until the specificity has reached whatever level appears to work best for that particular mechanism.

It is worth commenting that both these proposed mechanisms may be viewed as logic elements and thus offer an alternative physical embodiment for the "formal neuron" which was once much discussed by theorists (e.g. Blum, 1962), and based on the concepts put forwardby Hebb (1949). In particular however, it should be noted that Hebb himself was careful not to insist that neurones should constitute the basic embodiment, and that some other physical embodiment might conceivably serve the same sort of function — an opinion which he has recently confirmed (personal communication 1977). One important new feature here is, of course, the postulated string-like organization of the logical elements; and another is the vastly smaller size of the elements and their ensembles, leading to some momentous potential consequences which we will discuss in the next section. It also seems likely that molecular-sites could offer greater scope for precision and reproducibility, especially when used redundantly in synchrony — and yet still offer greater scope for plausible flexibility under appropriate circumstances.

This is not to say that neurones and their synapses do not perform such functions at all. Clearly they do operate in such ways — at least sometimes, (though even here their activity is presumably to be explained in terms of the massed action of molecular-scale phenomena). There is no obvious reason why both phenomena should not co-exist and intercommunicate within the one organism; after all it is difficult to see how the selective molecular-level activity discussed above could lead to effective muscular consequences without passing through a traditional action-potential stage. Nor should we dismiss the likely effect of DC or "quasi-static" audiofrequency electrical gradients on the mechanisms depicted above in *Fig 2.3/2*. These could well exert crucial modifying influences on the logic-transactions, thus constituting additional logical "input"; but their actual information-carrying ability would necessarily be much more limited than that of the postulated infra-red inputs to the same system.

Finally there is a rather different point to be made concerning the reception depicted in *Fig B2.3/2*. As has already been intimated, it is quite possible that the signals actually presenting themselves at such a system will bear little obvious resemblance to the signal-pattern as it was originally emitted — because of optical interference effects in transit. Dispersion due to wave-guide conduction is one such effect, and it is worth bearing in mind that such reproducible distortion may actually be *essential* if the incoming signal is to be compatible with (i) molecular configurations which are actually chemically possible, and (ii) the logical requirements of the task in hand. Seen in this light, the dispersion would indeed serve as a necessary translation from one "language" to another.

2.4 The apparent enigma of how experience might be chemically 'written down' — and a new solution made feasible if memory elements are molecular rather than only neural-synaptic.

Even if it be granted that all memory feats are performed by means of some form of matter-based encoding within the brain, the question of just how this might be accomplished appears to have been seriously neglected. At any rate no credible postulate for such "direct-writing" processes is known to the present author. This is perhaps not very surprising since it is difficult to see how one could ascribe (for instance) linear sequencing, precision, and reliability to a system of ultimately-diffuse elements like synaptic terminals though clearly they are adequate for explaining *some* phenomena.

The problem of linear-sequencing at least, can be accounted for by invoking the concept of the coded linear-molecule which we have just been discussing. This is of course encouraging, but this achievement in itself can only be regarded as partial success, since the question still remains: How did this coded representation of outside reality come to be recorded within that particular brain? In fact, the way that the question is posed is *probably misleading*; but let us, for a moment, explore the type of inventive reasoning which this wording of the question might lead to:-

“Normally the encoding of linear macro-molecules is directly guided by the specific coding on *other* macro-molecules. DNA controls the RNA encoding, and mRNA controls the protein encoding — these processes taking place at particular catalysing structures (RNA polymerase molecules, and ribosomes, respectively); (Miller, 1973). But suppose we could devise some system whereby an incoming *travelling signal* could dictate how a catalysing structure should construct a new linear macro-molecule. (Here the signal would replace the DNA or mRNA ‘template’, and the catalysing structure would serve a function similar to that of a magnetic ‘recording-head’ on a tape-recorder)”.

There are several obvious difficulties here:- Just how could the incoming signals “instruct” the catalysing structures, and with sufficient specificity and precision? Would there be an adequate (and sufficiently prompt) supply of the raw materials for constructing the new record — or would too many of these building operations fail because of an inability to keep up with the exogenously imposed signal? How could we explain the dynamics of such a system, notably the relative motion of catalysing structure and the newly-forming macro-molecule? And could this operate fast enough?

Granted that, if there are many alternative sites at which such molecular activity could find redundant expression, thus allowing for extensive failure amongst the occasional successes, there still remains ample room for doubt whether such procedures could *ever* work at all. And even if they do, we have still not begun to explain the second part of the total problem:- how to “know which call-sign to use” to retrieve this hard-won information once it has been stored.

The alternative adopted here instead, is the radical postulate that incoming impressions are *not* strictly-speaking recorded at all; — they must rather operate on arbitrarily[3] generated code-sequences, and “accept-or-reject” these as being a proper or valuable record of the on-going situation (including both perceptions and actions).

If this proposal seems too drastic, it should be recalled that this idea has long been implicit in the Piagetian concept that all learning requires initial *action* on the part of the learner — even for such apparently passive activities as visual or auditory perception, and such initial action must presumably be arbitrary (or genetically pre-determined). (Furth, 1969).

It should also be recognized that the “huge wastage” implicit in this type of Darwinian trial-and-error process, can only offer feasible solutions when huge populations of basic elements are freely available. Thus even though there are about 10^{10} neurones in the human brain, each with perhaps 10^3 synapses, it may nevertheless be doubted whether these would suffice on their own to encode the *variety* of actual experience, the *redundancy* needed for stability and precision, and also the postulated *huge reserve capacity required for ubiquitous trial-and-error*. If, on the other hand, the basic units of memory were on the molecular scale of size, then the effective population of elements would increase by many orders of magnitude so that, arguably, the wastage amongst

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[3] There might perhaps be some significant control over the statistical biases operating here, but these may be ignored for present purposes.

basic coding-units would then become an acceptable economic proposition for the living system as a whole.

Moreover the actual wastage of resources could well be minimal in such cases if the unwanted codings were still physically useful as raw material for generating yet other trial “mutants”. Such failures need not necessarily even be minimally broken down or denatured. It might suffice that they should simply fail to be granted the means for replication of their encodings. However it is difficult to imagine this sort of economy occurring within any neural-synaptic learning system which depended on a trial-and-error process of the type we are considering.

Thus most of the difficulties seem to disappear under the “neo-Darwinian” postulate. Raw codings are presumed to be manufactured complete with a context-sensitive “label-code” capable of producing retrieval if-and-when some particular aspect of the context recurs at a later date. If there is *anything* inappropriate about such a coding — including its “label” for activation/retrieval, given the actual form of signals at that point[4] — then it will simply be scrapped (statistically speaking) just as a non-adaptive mutant species will also ultimately die out; — also see Traill (1978b, Part C).

The consequences of such a suggestion are far-reaching. For just as the original Darwinian theory removed the need for teleological concepts in explaining how phylogenetic species originated, the present suggestion similarly removes the strict need for teleological concepts within mental activity itself!

It is not proposed to pursue these matters any further here, but their significance to the present discussion in this:- It now becomes reasonable to formulate problems concerning the mechanism of chemical memory-storage in terms of essentially simple emission and absorption phenomena without having to wrestle with the above probably-unanswerable questions of how the brain could operate like a tape-recorder or cine-camera. There will, of course, still be problems of specificity in such signals — potentially explicable in terms of key-like *patterns* of elementary signals — but we will have dispensed with the more mysterious aspects of memory, which would otherwise seem to call on us to explain the presence of a mechanism resembling the *consciously designed* artefacts of modern high-technology within a biological system! Thus we are saved the perplexing task of suggesting how such purposebuilt sophistication, with little scope for any performance other than total success or total failure, could have evolved gradualistically and pragmatically under the guidance of partial successes.

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[4] Note that, if dispersion does happen to be an important factor, then what will be a suitable “label” at one part of the optical path will not necessarily serve for other parts of the same path involving the same signal. A potentially important implication of this is that if no label can be constructed so as to be receptive to a given signal at one particular range, then perhaps some label *can* be found to coincide with that signal at *some other range*. Further aspects of this concept are developed in Traill (1978b, section C8.1).

Chapter 3

3. Transmission properties for various frequencies of electromagnetic signal within nervous tissue, and the special case of saltatory conduction

SUMMARY OF CHAPTER

This chapter provides a corroborative cross-check by making an independent analysis of the (saltatory) transmission-characteristics for myelinated axons presented with all frequencies from *1 KHz* to beyond 10^{14} *Hz*. Factors considered include: breakdown of circuit-theory assumptions for the very high frequencies, free transmission within the myelin dielectric, reflection at the co-axial boundaries, limited protection against water's absorption bands, evidence for signal-blockage, and possible artefact results. The conclusion is that audio-frequencies and infra-red frequencies are both suitable for such transmission, but not the frequencies in between.

3.1 A different evaluation in terms of the geometry and physics of tissues

The above discussion has primed us to be on our guard for evidence of signal activity involving frequencies much higher than those usually considered in connection with neural activity. So let us now turn away from the above predominantly *chemically*-inspired arguments and attempt, as far as possible, an independent "first principles" *physical* analysis of the properties of existing neurones as possible transmission-lines for electromagnetic signals. In doing so, we should try not to be biased by preconceived ideas about which frequencies are likely to be favoured in neural transmission — except perhaps for the reasonable assumption that we can confine our investigation to the wide range extending from *audio-frequencies* (about *1000 Hz*; *300 Km*) to just beyond the *near-visible* frequencies (about 3×10^{14} *Hz*; $1\ \mu m$).

As we are aiming to exclude chemical effects from this part of the study, we will therefore be primarily considering the chemically passive saltatory transmission across *myelinated* segments of nerve-fibres — using comparatively straightforward laws of physics. The objective then becomes one of deciding which frequencies could be expected to traverse existing myelinated segments, with tolerable efficiency. It will then be open to us to decide what incidental properties such frequencies might offer, and whether such properties are actually found in nature.

3.2 Some basic points concerning electrical theory

It is perhaps worth pointing out that, if we are to include very high frequencies in our calculations, then we must be rather more rigorous in our treatment of the basic electrical phenomena. For one thing we may no longer ignore magnetic induction effects (represented by *L henries* in circuit-theory treatments; or by the permeability, μ *henries/metre* in the equivalent Maxwellian treatment — see the symbol-list on page 6).

[Consider myelinated axons treated as co-axial cable, with length s (of *2 mm*, say), an inner radius of r_1 and an outer radius r_2; and take $\varepsilon \approx 2\times10^{-11}$ *Fd/m*, corresponding to a dielectric constant of *2.25*. Then we will have:-

$$|\text{ capacitive impedance }| \;=\; \frac{1}{\omega C} \;=\; \frac{1}{2\pi}\cdot\ln(r_2/r_1)\;\cdot\;\frac{1}{s\omega\varepsilon}$$

$$|\text{ inductive impedance}^{(5)}\,| \;=\; \omega L \;=\; \frac{1}{2\pi}\cdot\ln(r_2/r_1)\;\cdot\; s\omega\mu_0$$

Taking these equations as they stand (with some limited justification[5]), we then get

$$\text{the ratio}\quad \frac{|\text{inductive impedance}|}{|\text{capacitive impedance}|} \;=\; \omega^2 s^2 \varepsilon\mu_0 \;=\; (10^{-22})\,\omega^2$$

Consequently the magnetic-induction effects will be negligible if $\omega \ll 10^{11}$ *radians/sec*, (that is $f \ll 1.6\times10^{10}$ *Hz*), as is certainly true for the audio-frequency components normally contemplated. But clearly such an assumption is no longer valid for $f > 10^{10}$ *Hz*, or so].

Secondly, the much shorter wavelengths will mean that the time-lag effects (due to the finite speed of light, especially in a dielectric medium) will become important insofar as re-adjustments of phase relationships of the **E** and **H** vectors becomes possible within the propagation distances considered (about *2 mm* in this case). This means that the electrical signals can become irreversibly detached from their sources, like practical radio signals; (Skilling, 1962).

Furthermore, it is well known that, with increasing frequency, there is a decline in the effective penetration of current density into the interior of a conducting medium: “the skin effect”.

In view of these complications it is often more convenient to dispense with the usual circuit theory approach, at least for the high frequencies); and we may work instead from Maxwell’s equations and appropriate boundary conditions — thus treating the phenomena as problems in optics or radio-transmission.[6] This entails some conceptual re-organization:- Any signal-bearing *waves* should now be considered as travelling predominantly *within* the dielectric myelin, while any accompanying electrical currents are best considered as induced corrections within conducting boundary media, producing reflection effects which tend to trap the wave within the myelin. But although this sort of conceptualization is applicable even to that paradigm of elementary circuit-theory: a direct current flowing through a wire (Heaviside, 1893, chap 4; Skilling, 1962, page 133), it is generally less bothersome to retain the normal circuit-theory conceptualizations for the lower frequencies in which the transmission-distance is less than the wavelength order-of-magnitude (Skilling, 1962, chap XI); i.e. within the “near-field region” (Walter, 1970).

For a physical analysis we may distinguish three different media: the myelin itself (and the lipid interior of membranes); the surrounding ionic solutions (here assumed to have the same *physical* properties inside and outside the axon); and any special layer which might exist between the other two types of medium. We shall now consider how these three media and their interfaces might affect transmission, starting with the latter somewhat-speculative boundary medium.

3.3 Possible boundary reflecting-layers: their nature and implications

Although it seems likely that lipid membrane surfaces are liberally bestowed with protein molecules, this does not in itself guarantee that they have any significant effect on the optical

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[5] But see (1980) note on page 6. —— [Footnote added in 1980; RRT]

[6] This Maxwellian approach is, in fact, more correct. [RRT 2006]

properties which we are now considering. Nor, for many frequencies, is there any *need* to postulate any such effect: audio-frequency reflection (if applicable) can be perfectly well explained in terms of the conductivity of the ionic aqueous solutions, and visible frequencies could be explained as Total Internal Reflection. However, for infra-red frequencies there arises the vexing problem of drastically high absorption in water (Robertson, Curnutte, and Williams, 1973) — due to energy dissipation via hydrogen-bonding; (Magat, 1948; Chamberlain, *et al.*, 1966).

Thus if infra-red is to be noticeably reflected at all from the myelin-boundary region, it would seem that some sort of special boundary layer must be responsible. One possibility is that the normal chains or rings of water-molecule dipoles (Kistenmacher, Lie, Popkie, and Clementi, 1974) might somehow be broken up or constrained under the prevailing boundary conditions — static, dynamic, or both; (and the absorption spectrum might then become *locally* more like that of adsorbed water, (Little, 1966)). As part of this hypothetical phenomenon — or as a separate effect in its own right — it is conceivable that an electrostatically induced concentration of charged particles at the boundary might significantly assist reflection.

Rather more attractive however, is the suggestion by Cope (1973) that there is a boundary layer of protein which is highly conductive for high frequencies. Cope goes further by suggesting that the protein concerned is *cytochrome oxidase*, and that it might conceivably be superconducting at normal temperatures under favourable circumstances. (See Cope for further references, pp 638-639).

In the light of these possibilities, it is instructive to re-examine critically the evidence that saltatory conduction is blocked by greatly increasing the resistance in the external electrolyte; (reviewed by Stämpfli, 1954). At that time there was concern to establish whether any or all of the current might flow through a hypothetical “tunnel” below the outer surface of the myelin. Our present concern, by contrast, is to clarify whether any or all of the reflection-inducing conductivity occurs in a supposed boundary layer; — and if so, at what frequencies, and what combinations of these frequency components might be indispensible for various specific signalling purposes. In short then, the whole issue may be very much more involved than previously supposed.

At first sight these experiments seem to show that *the signal* is transmitted by audio-frequency components — any other frequency components being redundant. But such a conclusion can be criticised on several grounds. To start with, we may well be dealing with a cable which normally transmits a highly multiplexed combination of *many signals;* and by testing for audiofrequency components only, we may miss observing many other activities which may be going on. Then most of the work has been done on peripheral or spinal nerve-fibres, whereas the effects postulated in chapter 2 (involving other frequencies) might be concentrated in the neocortex and yet be absent elsewhere.

Next there are various non-obvious ways in which the experimental procedures might have stopped high frequency transmission (at the supposed boundary layer) at the same time as audiofrequency components were stopped by obstructing the external electrolyte. Ranck (1975) warned that *exposure to air* is likely to make important electrical changes in brain tissue within a few minutes, and that such effects have not generally been taken into account. Then those experiments attempting a rigorous control of the external circuit have often involved bringing the nerve-fibre into close contact with an unfamiliar dielectric — petroleum-jelly or oil, etc. (e.g. Huxley and Stämpfli, 1949, page 318) — which might act as a disturbing “echo-chamber” for leaking signals. (The *normal* external dielectric would of course be water, which would readily “kill” any unwelcome leakages of signal in the infra-red range).

Another interesting question is raised by an early statement from Tasaki (1939):-
"*... in the medullated nerve fiber, complete desiccation of the medullated region alone does not inflict upon the fiber any noticeable change in excitability or conductivity if all the nodes [of Ranvier] of the fiber are kept in Ringer's solution.*"

This appears to be at variance with what was soon to become the orthodox view that it is essential to have a closed circuit through an 'external' medium or capacitance.
Thus Stämpfli (1954, page 107), having explained precautions against capacitive leakage writes:

"*The resistance of a film of saline* [assumed to be around Tasaki's 'desiccated' fibre ?] ... *is barely high enough to cause a block ...*".

This difficulty was seemingly resolved by
"*using internodes ... washed with isotonic sucrose before drying.*"
Such treatment succeeded in abolishing the signal transmission.

The trouble is, of course, that no thought could have been given to problems of controlling for infra-red frequency components, nor to the implications of any boundary-layer mechanisms whose functioning might well have been disrupted by the sucrose washing. In part though, the difficulty is merely a semantic one: if we were to define any boundary-layer currents as being 'external' (*along with* those in the external electrolyte), then we could accept the above Stämpfli summary as being correct in spirit — though a trifle misleading.

It is to be hoped that, in due course, further experimentation will resolve these various issues. If there happened to be any inter-paranodal supportive interaction between different frequencies, then the methodological problems could be formidable; but it seems unlikely that such phenomena would occur at active nodal or paranodal sites.

3.4 Transmission possibilities for a co-axial cable of myelin in direct contact with homogeneous aqueous solutions

Let us start with a circuit treatment of transmission at the lower frequencies. It is clear that as the frequency increases, more and more of the signal will leak through the myelin dielectric due to capacitance effects; but it will be instructive to look at this quantitatively to roughly determine the band-pass limit for such near-field region signals.

To this end, we may compare the capacitative impedance Z_c, with the resistance of the internal core of axoplasm, R_{int}. (For our present order-of-magnitude purposes we can ignore the details of transitional cases in which Z_c and R_{int} are of comparable magnitude thus complicating the circuitry; c.f. Katz (1966, page 74)). Thus we will have (using modern units):-

$$|Z_c| = \frac{1}{2\pi} \cdot \ln(r_2/r_1) \cdot \frac{1}{s\omega\varepsilon}$$

where (r_2/r_1), the ratio of the radii, can be taken as roughly 1·5 (Boyd and Kalu, 1973: see Fig 4/2 below); and s is the length (expressed in metres).

Thus with $\varepsilon \approx 2\times10^{-11}$ Fd/m again:-

$$|Z_c| = \frac{10^{10}}{\pi . s\omega}$$

Meanwhile the resistance is given simply as

$$|R_{int}| \quad = \quad (\text{axoplasm resistivity}) \cdot \frac{s}{\pi(r_1)^2}$$

Taking the axoplasm resistivity as *0·30 ohm-metre*, the lower value given by Katz (1966, page 47), we obtain

$$\frac{|Z_c|}{R_{int}} \quad = \quad (5{\cdot}3 \times 10^9) \quad \cdot \left(\frac{r_1}{s}\right)^2 \cdot \frac{1}{f} \qquad \qquad \text{since } \omega = 2\pi f$$

Now substituting realistic values of $r_1 = 7\,\mu m$, as for the larger group I axons (Boyd and Kalu, 1973); and $s = 1\,mm$:

$$\frac{|Z_c|}{R_{int}} \quad = \quad \frac{2{\cdot}6 \times 10^5}{f}$$

so that capacitive leakage will start to predominate when the frequency rises to about *260 KHz*; (*65 KHz* if $s = 2\,mm$; or going the other way *1·04 MHz* if $s = ½\,mm$). Then again, these frequencies will be lower for narrower axons.

It follows from this that frequency components of about 10^6 *Hz* or more are unlikely to survive neural transmission to any significant extent *unless* they have wavelengths short enough for them to transcend the near-field region conditions. They would then become able to maintain locally recognizable *radiated* waves within the dielectric medium; and of course this implies infra-red frequencies with wavelengths reasonably comparable to nerve-fibre diameters. (The only other scope for raising the band-pass frequency would seem to be to postulate enhanced longitudinal conductivity — presumably invoking some sort of boundary-layer conductance effective at the relevant Radio Frequencies. This would seem to be rather unlikely even if we accept that such boundary-layers exist and are effective for Infra-Red, as the latter IR transmission could reasonably be achieved using semi-restrained electrons, whereas the former Radio Frequency conduction is unlikely to be realized without *free* electrons or ions).

Even without a boundary-layer we will eventually expect to reach a frequency at which orthodox Total Internal Reflection can operate within the myelin. Thus we may take Finean's (1967) value of *1.66* for the refractive index of bi-lipid layers, along with the evidence that the incidence of absorption bands for lipids is minimal in this infra-red range (cited by Cope, 1973, page 636) — implying a *constancy* for the refractive index throughout the range (Jenkins and White, 1950, chapter 23). We may contrast this constant value of *1.66 for myelin* with the variable refractive index for *water* as plotted by Ray (1972) and by Robertson *et al.* (1973). On these figures we can infer that Total Internal Reflection will start when the frequency rises to about 5×10^{12} *Hz* (wavelength of *60 μm*) and will continue at least as far as the visible frequencies.

However this notional reflection will not, in itself, guarantee the waves against the water absorption bands (also plotted by the same authors) assuming that the water's properties immediately adjacent to the supposedly bare myelin are exactly the same as the properties of the water elsewhere. (On the other hand, as suggested above in section 3.3, one might speculate that the "boundary layer" of water might have a *specially circumscribed* hydrogen-bond structure or suchlike — suppressing some of the normal energy dissipation. This could then be the basis for a possible boundary-layer explanation *alternative to* or *additional to* Cope's (1973) protein layer).

But if the absorption bands cannot be circumvented at all, then it looks as though there can be no dependable resumption of transmission until the wavelength falls to about *2μm* (just short of the visible); because even the most likely wavelength before then, *4.1 μm* (Robertson *et al.*, 1973), is absorbed at a rate somewhat greater than *20 nepers/mm* (*200 nepers/cm*).

As for the wavelengths mentioned in *Table 2.2/I* as being potentially important on chemical grounds, the *20μm* chain-deformation band is probably an absolute "non-starter" with about *260 nepers/mm* , and of course the *3μm* OH-stretch which is one of the main water-absorption modes. But all the other bands have at least part of their range subject to absorption of less than *60 nepers/mm*. Thus although none of these frequencies is likely to be transmitted successully if there is absolutely no boundary-assistance, yet the figures for absorption are mostly not impossibly high for the distances involved, and a moderate amount of boundary-assistance could quite plausibly bring losses down to within tolerable limits — without the need for invoking such extremes as superconductivity.

In fact one can also invoke another factor which presumably reduces the impact of water absorption. It should be born in mind that for such a myelin wave-guide, much of the wave-front will be travelling *within the myelin* at any given instant, and *not* in the aqueous media. Thus it would appear that the *effective absorption* will only be a fraction of what we would expect for transmission through water alone. However since such attentuation significantly complicates the mathematics of wave-guide transmission (Skilling, 1962; Waldron, 1969; ....), we should be cautious in our assertions on such matters. Anyhow such a quantitative analysis will not be attempted here.

It might also be remarked, in retrospect, that such high absorption is probably *essential* within the surrounding medium to prevent the uncontrolled cross-interference of signals — and indeed to establish consistent signal paths to comply with the requirements suggested above in section 2.4. (In this role, the aqueous surroundings may be seen as roughly analogous to the insulation used in DC circuitry). Moreover such indulgence in near-threshold extremes (between conduction and non-conduction) is exactly what we should have expected for any *control system* capable of switching signals on and off — under the influence of apparently trivial phenomena. In this case, such weak-but-influential control-signals could be expected to marginally alter the optical absorption past some threshold value, thus producing a magnified effect. (Semi-conductor technology, vacuum tubes, and "formal neurones" also illustrate the same basic principle).

3.5 Summary of basic transmission characteristics expected in nerve-fibres — on theoretical grounds

The predictions of band-pass characteristics must depend to some extent on hypothetical boundary-layer media between the myelin and its aqueous media. But it looks as though the gross electromagnetic bands are (i) Audio-Frequencies up to about 10^5 *Hz*, and (ii) "Optical" frequencies — probably including at least some bands of infra-red, provided there is a moderate amount of boundary-layer assistance in enhancing local conductivity *and/or* in protection from normal water-absorption bands, (this protection being due to the supposed boundary layer or due to the myelin itself). In view of the apparent wide hiatus between these two gross bands, it would not be surprising for one of them to have been overlooked by experimentalists.

Chapter 4

4. The second-lowest mode of transmission in co-axial myelin ($H_{l,0}$): optical dispersion of infra-red

SUMMARY OF CHAPTER

This chapter argues that existing myelinated segments could also act as dispersive media, similar to those postulated in chapter 2, by using "higher vibrational modes" within the myelin.

Within a co-axial wave-transmitting medium, many vibrational modes are theoretically possible. Of these, the basic "*TEM*" mode[7] is the one most used in electrical engineering, and cables are designed such as to be too small for any higher modes to be able to develop — given the frequencies expected to be used. In principle *all* frequencies may be propagated along such a cable in the basic *TEM* mode, and ideally their velocities will all be the same as they would be in the same material medium if it were unbounded. In practice though, this ideal will be imperfectly attained, to the extent that boundaries fail to be perfectly reflecting.

Other vibrational modes of propagation become possible when the wavelength becomes short enough for component waves to interact simultaneously such that their summated **E** field is always zero *tangentially* to all the (ideal) conducting surfaces.

There is a denumerably infinite number of such modes possible, but the lowest energy one (and therefore the one likely to be first encountered) is the $H_{1,0}$ *coaxial* mode with its **E** field wholly Transverse at all points; (hence the alternative name: "$TE_{1,0}$"). For a given cross-section, this **E** field follows one diameter right across in a continuous direction (apart from the interruption caused by the central core), and splays out on either side of this diameter such as to meet all reflecting surfaces at right angles; while at vibrational *node-planes* (distributed regularly along

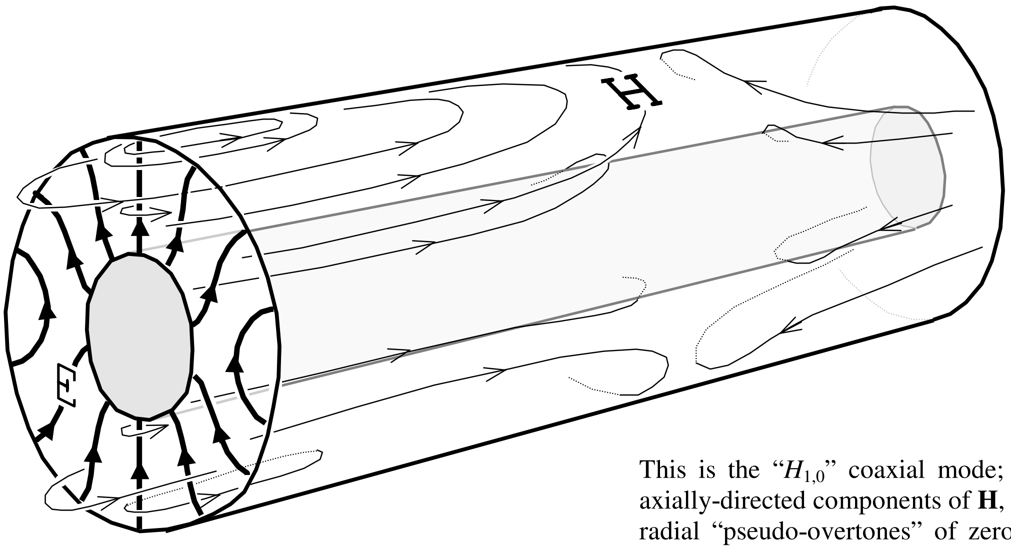

Fig 4/1

Schematic diagram of the first non-*TEM* propagation mode in a co-axial cable (such as a myelinated axon). This is the "$H_{1,0}$" coaxial mode; (so called because it includes axially-directed components of **H**, an angular periodicity of 1, and radial "pseudo-overtones" of zero). It is also known as "$TE_{1,0}$" (because its **E** is transverse only, as in the case of *TEM*).

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[7] *TEM*: "Transverse Electric *and* Magnetic components". I.e. neither **E** nor **H** vector has any component parallel to the axis of the cable at any point, so the direction of propagation of the wave's energy (the Poynting vector, which is perpendicular to both **E** and **H**) *will* everywhere flow parallel to the axis. (This is, of course, an idealized concept which assumes perfect reflection at the boundaries).

the axis at any given instant), the cross-sectional field vanishes and re-appears with reversed direction beyond each node-plane. See *Fig 4/1*.

Meanwhile the **H** field forms a band of roughly concentric-elliptical closed loops around the two ends of the centre-diameter region midway between consecutive node-planes of the **E** field, such as to keep **H** perpendicular to **E** at all points.

Quantitatively, the formulae are expressible in terms of Bessel functions (including "second type" or "Neumann" functions). Some cut-off values are given in Waldron (1969, page 250) and applied in *Fig 4/2*, though it will usually suffice to use sinusoidal functions of the radius instead: in effect treating the cable as if it consisted of two separate rectangular wave-guides, each *m* in *height* (the thickness of the annular gap: $r_2 - r_1$), half the average circumference in *width*, and carrying a $TE_{0,1}$ *rectangular* wave-guide mode (with vertical **E**).

The cut-off frequency will then occur when the wavelength grows so that the wave becomes trapped into being a standing wave "across the width of the rectangular guide" (actually around the sector of a semi-annulus). This happens when the wavelength (λ_{med}) rises to twice the "width" [$w = \pi$(average radius)]: analogous to the fundamental standing wave in a stretched string of length *w*.

So now we have $\lambda_{med} \leq 2\pi(r_1 + m/2)$; where λ_{med} is the actual wavelength within the medium. The results are shown graphically in *Fig 4/2*, indicating the maximum acceptable values of λ_{vac} — the corresponding wavelength *in vacuo*, here derived using the above-mentioned value for the refractive index of myelin, *1.66*, so that $\lambda_{vac} = (1.66)\,\lambda_{med}$. The same diagram also roughly indicates Boyd and Kalu's (1973) statistical findings for the dimensions of afferent cat axons.

From this plot we can see that under ideal conditions the absolute maximum wavelength that could exist in this vibrational mode would be about *95 μm*; (though if such a wave is to differ appreciably from being a standing wave, we should roughly halve such values). Also $\lambda_{vac} \leq 40\ \mu m$ (for group II), $\leq 27\mu m$ (group III) and $\leq 7\mu m$ (for the smallest fibres of group III). By comparison, we may recall that the bands most likely to survive water-absorption were: *<2.7μm*; *3.5 to 5.8μm*; *6.9 to 9.1μm*; and *>100μm*; (Robertson, *et al.*, 1973); — and of these we can see that all but the last seem to satisfy the geometrical restrictions for our particular non-*TEM* vibrational mode — even for most of the group III fibres.

It was suggested in chapter 2 that dispersive media could serve a useful purpose in signal analysis. The objective of this present chapter has been to investigate the possibility that myelinated axons could operate as just such dispersive media by carrying signals in a non-*TEM* mode. The results of the analysis indicate *that such dispersion is indeed always possible* for existing myelinated axons of the type considered here — provided we accept infra-red transmission as plausible, and provided the anisotropic optical properties of myelin do not radically affect the issue; (Cope, 1973, page 637).

Logically speaking this can be regarded as no more than suggestive: the mere fact that there is a capacity-for-function does not prove that this capacity is used. On the other hand though, evolutionary pressure tends to make sure in the long run that any chance property is explored for its potential usefulness; so it is a tolerably good rule-of-thumb in biology to expect that a mechanism like the present one will have found an application — at least in some animals.

As a further word of caution, it should be born in mind that the above quantitative analysis assumes that the myelin has a *circular* cross-section — a condition which does exist sometimes, but which must be regarded as exceptional in practice; (Boyd, personal communication, 1977). For circuit-theory types of analysis based on Rushton (1951), such distortions should make little difference especially if we use directly-applicable measurements of area and perimeter rather than "diameter" (Kalu, 1973); but these same distortions are much more likely to complicate any similar analysis based on wave-guide theory, as suggested by the results of distorting a co-axial system in a slightly different way (Wait and Hill, 1974). Indeed such differences in supposed properties might usefully be used to *test* the current theory that optical transmission exists within myelin. Meanwhile, any limitation of the above precise calculations to one particular subset of the nerve-fibres merely suggests that we will have to do separate detailed analyses for other shapes; but the general principles of wave-guide conduction and dispersive distortion will almost certainly still apply (if they apply anywhere), and perhaps they will apply with even greater strength in view of the fact that irregular cross-sections will probably discourage the non-dispersive *TEM* mode, (Wait and Hill, 1974).

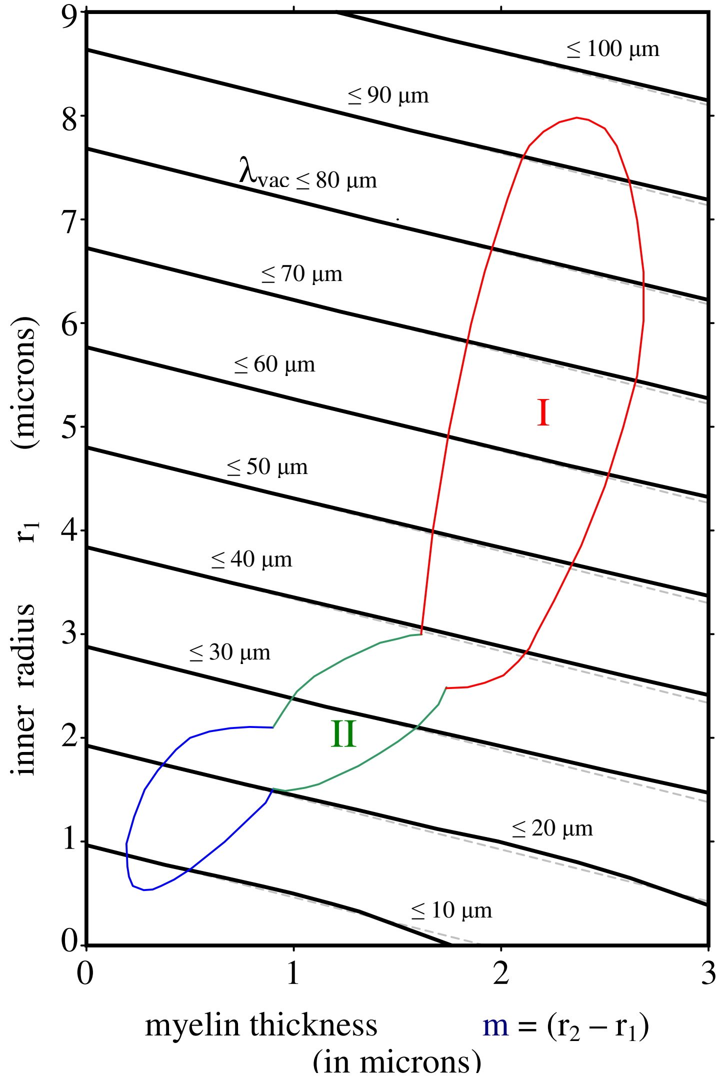

Fig 4/2

Calculated basic propagation characteristics of various nerve-fibre configurations using the coaxial-$H_{1,0}$ vibrational mode and assuming idealized geometrical and reflection conditions.

The curves indicate the limiting wavelengths for $H_{1,0}$ mode propagation in any nerve-fibre which happens to have that particular cross-sectional geometry — as given by the coordinates.

These curves are closely approximated by the straight-line formula

$$\left(\frac{1}{n} \cdot \lambda_{vac}\right) = \lambda_{med} = 2\pi \text{ (average radius)}$$

where n is the refractive index of the myelin, *1.66*; and these straight-line approximations are shown by the grey dashed straight-lines. (The error vanishes at the left-hand end).

As $r_1 \rightarrow 0$, this coaxial mode approaches the limiting case of the *cylindrical*-$H_{1,1}$ mode, with the relationship between m (now $\rightarrow r_2$) and λ being determined by the first non-trivial solution of

$$J_1\left(\frac{2\pi}{\lambda_c} \cdot r_2\right) = 0;$$

where λ_c is the cut-off value of λ_{med}, and $J_1(\ldots)$ is a Bessel function. Nevertheless the straight-line approximation is still correct to within about 8%.

As a comparison, the enclosed coloured area approximately indicates the actual distribution for most of the afferent nerve-fibres (Groups I, II and III) as observed by Boyd and Kalu (1973) — accumulated here from two closely similar diagrams. It should be born in mind that dispersion will be greatest as λ approaches its cutoff value; so if processing *depends on* dispersion in this $H_{1,0}$ mode, then group III fibres are the most likely sites for such activity (given the values for likely frequencies in Table 2.2/I, omitting the *20µm* and *3µm* bands on the grounds of high absorption — see section 3.4). The rules of the game will, of course, be conveniently different for other vibrational modes.

Chapter 5

5. Evolution of communication methods: suggested extensions to Bishop's two stages

SUMMARY OF CHAPTER

This chapter speculates on the evolutionary development of communication systems in animals, and suggests that the basic elements of infra-red transmission may be very ancient and primitive.

Bishop (1956) argues not only that there are two types of neural activity — graded versus all-or-none, but also that the graded response is the more important, ubiquitous, and primitive: If animals were to be able to increase in size without losing control of their own bodies, it would have become necessary to discover a new communication mechanism which could cope with the larger distances without serious decrementation of the signals.

In the light of our above investigations this raises the more general question of the *total* evolutionary process of communication systems within organisms, including any *precursors* of the graded response — in protozoa or viruses. As Bishop himself suggests, the graded response is likely to occur only after several stages of evolution in the cell *membrane*, involving the prior successive developments of: passive depolarization, active depolarization, and selective sodium-ion permeability — respectively. How then was control exerted within the virus or isolated protozoon? How indeed is control exerted in the *interior* of any largish cell, isolated or not?

Fairly obviously *the most primitive* method would be phonon-or-electron transfer or some other form of *direct chemical contact* such as that inherent in the production of mRNA in DNA-viruses and cells lacking nuclear membranes (prokaryotes). Next *chemotaxis* (spatial gradients of the above) might be considered to be a second evolutionary innovation closely related to the first, and a number of control functions have been attributed to it (Trinkaus, 1969), though it is not entirely clear just how such gradients could operate effectively over the distances envisaged.

In any case it is questionable whether diffusion and chemotaxis on their own could account for all cellular control before the supposedly delayed advent of specialized cell-membranes. However it is worth bearing in mind that chemical interactions are ultimately to be explained in terms of electrostatic, electrodynamic-photon, acoustic phenomena, and charge transfers; and that at least some of the electrical effects *are* readily *transmittable* in favourable circumstances. Such emissions from different ultramicro sites might be undirected and statistically non-interacting, at least in primitive systems; or else some degree of laser-like synchronization might develop (as perhaps in the phenomena discussed by Fröhlich (1968, 1975)), thus potentially giving a directed beam — perhaps from several coordinated sites on a plane-like surface such as the nuclear membrane or endoplasmic reticulum. As for the *synchronization* of this "laser-or-aerial" source, conjugated double bonds might well be involved as conductors of an electronic trigger-signal, (Szent-Györgyi, 1968); or the triggering could be performed by phonons or excitons.

But from amongst this assortment of speculations, let us rescue the point which is of immediate relevance:- that such transmitted quanta may be considered as an evolutionary *extension* of simple "contact chemistry" — into "chemistry at a distance" which could often simply be described as photochemistry applied to biological needs (of which *photo-contact between fireflies* is another, more tangible, example). By the same token, such communication would then appear to be the *third-most-primitive* method for exerting control or integration-of-function. It is likely that the frequencies most involved in such signalling would be in the infra-red region — because, as we saw in chapter 2, these are the frequencies most involved in relevant molecular absorption and emission bands.

(We should not be surprised to find this radiation phenomenon in both this primitive position and also in the highly sophisticated saltatory conduction. This dual identity would seem to serve as a further illustration of Bishop's contention that new specializations tend to co-exist with the more primitive mechanisms — or even to *incorporate* them, as seems likely here).

Next in the hierarchy we might reasonably place the ("graded") *trans-membrane potentials* — tentatively at *position four*, and not position one as suggested by Bishop. Presumably the effect of these graded potentials would be to exert electrostatic parameter-control over ongoing chemical processes, of which sodium-ion release would be just one example.

As an interesting possible case of evolutionary recapitulation[8], it is instructive to compare *these* evanescent effects with the *smaller scale* evanescent near-field-region electromagnetic effects presumably associated with the chemical interactions of primitive communication, mentioned above.

The next stage or stages would presumably involve the development of elongated axons, all-or-nothing action potentials, and synaptic mechanisms — along well known lines and with evolutionary significance as outlined by Bishop (1956). And this "self-sustaining" propagation might be seen as a formal recapitulation (functionally but not physically) of the *radiated* chemical effects postulated above — *viz.* infra-red effective beyond its near-field region, propagated into a single bi-lipid layer.

But we should also go one step further and consider *myelination* as an additional evolutionary breakthrough. It is commonly assumed that the sole or main function of myelination is to speed up activity in the relevant axons; and certainly several important consequences follow from this rapidity:- It reduces refractory periods (allowing spike-patterns more scope for message-coding); it allows for much narrower axons; and it probably affects any hologram interference patterns in some significant way — even assuming they were to operate entirely on *audio*-frequency components.

But it has also been suggested above that myelin may have another important function — that of acting as a dispersive medium to assist in the effective decoding of the more complex signals used by the more adaptable higher animals. The evidence for this suggestion is no more than circumstantial; and it is simply offered as a working hypothesis, as a step towards filling a hiatus in existing explanations.

We should also hasten to add that even if such "higher mode" dispersion does occur in some circumstances, there is no reason why it should always occur or predominate, or why it should *always* have this signal-analysis function. In many spinal pathways such as pyramidal tracts, uncomplicated speed of transmission is of prime importance, so that modes such as $H_{1,0}$ could well be superfluous, even though they might be important elsewhere.

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[8] Interestingly enough, man-made cable-communications also appear to have evolved in a similar sequence. Early emphasis was on "low frequencies" (simple non-modulating Morse signals) within the near-field region, complete with attendant problems of capacitive loss and evanescent signals (Thomson, 1855b). The concept that electromagnetic phenomena could be self-sustaining in their propagation (and therefore be classified with light) had to wait another decade (Maxwell, 1865); and this still required much development in the context of waveguides (Heaviside, 1893). Today we not only use Radio-Frequencies and micro-waves in co-axial cables, but we also go on to still higher frequencies in our use of *fibre optics* for telecommunications — an application which became a commercial reality during the original preparation of this text, (see the advertisement in *the Economist,* **262**(6966), 30-31; 5 March 1977).

Chapter 6

6. Other related architecture in brief: glia, paranodal regions, and cell-body interior

Having outlined the postulated sequence of evolutionary breakthroughs in the principal techniques of control, we may now return to have a special look at further likely implications of the supposed infra-red based processes — in both the primitive and the myelin-conduction versions.

It seems likely that infra-red components of a signal will be “steered” into their *own* reception sites, which need not have any close connection with audio-frequency reception sites.

For one thing, it seems likely that the most natural reception sites for infra-red would be in the *para-nodal regions* (rather than only near synapses as we might expect for audio-frequency components). In this case it seems probable that *glial cells* will be very much involved in view of their close anatomical attachment in these regions (Livingston, Pfenninger, Moor, and Akert, 1973).

If glia *are* involved in this way, then we may be in a position to gain some further insight into the importance of myelination in infant development (and in evolution), and the devastating effect of de-myelinating diseases such as multiple sclerosis.

As for the intra-cellular activity: With absorption reaching about *60 nepers/mm,* we might expect a tolerable signal range for “unprotected” signals to be about $(1/60)\ mm = 17\ \mu m$. For distances greater than this it is conceivable that bi-lipid structures such as the endoplasmic reticulum may serve as protective communication channels; though note that for simple isolated bi-lipid layers, the frequency range is restricted to the near-visible end of the infra-red spectrum — with higher energy quanta. (It is just such bilipid layers which Cope (1973) undertakes to study).

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The "1899" = date of the original publication in the original language;
while the last-mentioned "2000" = date of the version principally referred to.

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