PROMOTION AND LIMITATION OF GENETIC EXCHANGE

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Exchange of genetic material has widely been observed in practically all living organisms. This suggests that genetic exchange must have been practised since a long time ago, perhaps ever since life has existed. The rules followed by nature in the exchange of genetic information are studied by geneticists. However, as long as the chemical nature of the genetic material remained unknown, genetics remained a rather abstract branch of the biological sciences. This gradually began to change after Avery et al. (1944) had identified DNA as the carrier of genetic information. Their evidence found an independent support by Hershey and Chase (1952), and it was accepted by a majority of biologists by 1953 when Watson and Crick (1953) presented their structural model of DNA. Hence it was clear 25 years ago that very long, filamentous macromolecules of DNA contained the genes. As is usual in fundamental research, the knowledge acquired pointed to a number of new important questions. Among them were those on the structure and function of genes, but also those on the molecular mechanisms of exchange of genetic material.

It is at that time, in the fall of 1953, that I joined more or less by chance a small group of investigators animated by Jean Weigle and Eduard Kellenberg. One of their main interests concerned the mechanisms of genetic recombination. Feeling that the time was not ripe to carry out such studies on higher organisms, they had chosen to work with a bacterial virus, the nowadays famous bacteriophage lambda (A). It is interesting to see today how knowledge acquired in work with phage λ should later strongly influence other research in molecular genetics. In this lecture I would like to trace back to the origin of some discoveries made in the work with A and point to their importance for subsequent investigations. But let met first define in more general terms what I mean by genetic exchange.

Escherichia coli and other bacteria carry all their genes on a single, very long DNA molecule, except for occasional cases when bacteria have one or several additional, much shorter DNA molecules, called plasmids, endowed with the ability of autonomous replication. A bacterial strain harbouring besides its chromosome a fertility plasmid F can at times donate by conjugation a copy of its F plasmid to a recipient strain. The F plasmid then establishes itself in the recipient cell as an autonomous plasmid, and it will be propagated in its new environment. The donor strain has thus exchanged genetic information with the recipient strain, and in this case

the genetic material transferred had not existed in the recipient strain before the conjugation. We also note that the exchanged material replicates autonomously, and it does not need to be integrated into the bacterial chromosome. Therefore, this is an example of reassortment of DNA molecules.

This situation contrasts with the one encountered in the so-called general recombination. Here two individuals exchange homologous genetic information. An example for this is also seen in bacterial conjugation. With a low probability, the fertility plasmid F can integrate into the host chromosome. In conjugation, the resulting strain (= Hfr strain, for high frequency of recombination) transfers a relatively long segment of a copy of its own chromosome to the F^- recipient cell. Maintenance of the information acquired by the recipient depends on its integration into the recipient chromosome, and this integration usually follows the rules of general recombination. This means that recombination depends on the finding of homologous sections on the two interacting genomes; and homology means identity in the nucleotide sequences, with an allowance made for rare exceptions to this rule at sites of mutations, which in fact allow the geneticist to explore these phenomena. Therefore, an exconjugant recombinant genome is a hybrid having received part of its information from one, and part from the other parent. The total information content of the hybrid is the same as that of each parent. The same rule holds true in general recombination between two bacteriophages of the same strain, and it was in work with bacteriophage A that physical exchange between the two parental genomes was experimentally demonstrated to occur in general recombination (Kellenberger et al., 196 1; Meselson and Weigle, 196 1).

We know that the molecular mechanism of general recombination is quite complex and depends on a number of specific gene products. Some of these proteins also carry out key functions in DNA replication as well as in DNA repair.

The studies of bacteriophage lysogeny in the 1950's ripened the concept that other mechanisms of molecular exchange between DNA molecules must exists. When bacteriophage λ infects a bacterial host cell it can either reproduce vegetatively to yield a progeny of phage particles or it can lysogenize the host cell. In the latter situation the infected most survives, and it will accept the A genome as a part of its own chromosome. This is similar to what we have discussed as reassortment of DNA molecules. However, the A prophage, as is called the λ genome carried in a lysogenic cell, does not replicate autonomously and its maintenance depends on its integration into the host chromosome, which usually occurs at a site close to the genes determining galactose (Gal) fermentation (Wollman, 1953; Lederberg and Lederberg, 1953; Jacob, 1955). Lysogenic bacteria can be induced to phage production, and in this process the prophage gets excised again from the host chromosome. Morse et al. (1956 a,b) observed that phage lysates obtained by such induction of A-lysogenic Gal+ bacteria were able to render Gal- bacteria Gal+. This phenomenon is called specialized

phage-mediated transduction. The authors mentioned that some of the Gal+ tranductants obtained did not produce plaque forming phage upon induction, although these bacteria were immune to superinfection with λ, a property usually displayed by A-lysogenic bacteria. At that time I studied A prophage mutants with defects in genes expressed in the cycle of vegetative phage reproduction. Therefore, Gal+ transductants as just described were a welcome enrichment of my materials to be studied.

Let me now show what I still consider a simple, straightforward experiment published in my Ph. D. thesis exactly 20 years ago (Arber, 1958). A phage λ lysate transducing the Gal+ characters at high frequency (HFT lysate) was used to infect a Gal- bacterial strain at various multiplicities of infection of phage particles per cell, and the surviving bacteria were tested for their Gal and lysogenicity character (Fig. 1).

As expected, the overall probability of an infected cell to become lysogenic remained constant in the range of multiplicities of infection below 1, i.e. the number of normal-lysogenic bacteria linearly dropped with decreasing amounts of phage added (curve 3 of Fig. 1). This curve is exactly paralleled by the one (curve 1) representing Gal+ transductants found to be immune to superinfection with λ, but which produced no plaque forming phage upon induction. In contrast, the number of Gal+ transductants which both were λ-immune and produced plaque forming phage upon induction (curve 2) is proportional to the square of the multiplicity of infection (Arber, 1958; Arber et al., 1957).

The interpretation given to these observations was that the HFT lysate used was a mixed population of A phage particles: (a) normal A phages and (b) λgal transducing phages which were defective in their capacity to reproduce serially and thus to form plaques, but which were still able to lysogenize even after single infection, although they did so with reduced probability. This interpretation found support in a number of additional experiments, which I would not like to rediscuss now. In summary, by 1958 it was shown that in the excision of A prophage from the bacterial chromosome errors could sometimes produce aberrant phage genomes having acquired a segment from the host genome and having deleted from the A genome a segment carrying essential genes for phage reproduction. A molecular model to explain both precise A excision and the illegitimate formation of Agal was drawn by Campbell (1962), who had also brought very important experimental contributions to this field. The analysis of a large number of independently produced λgal genomes made it clear that recombination within DNA molecules, and by extrapolation also between DNA molecules, occurs sometimes at more or less randomly chosen sites, and hence not selected on the basis of extended regions of homology. Obviously, the likelihood for such recombinants to be viable is relatively small, and nature seems to limit their production to a level several orders of magnitude below the level of general recombination. In evolution, however, this kind of illegitimate recombination may be of great importance.

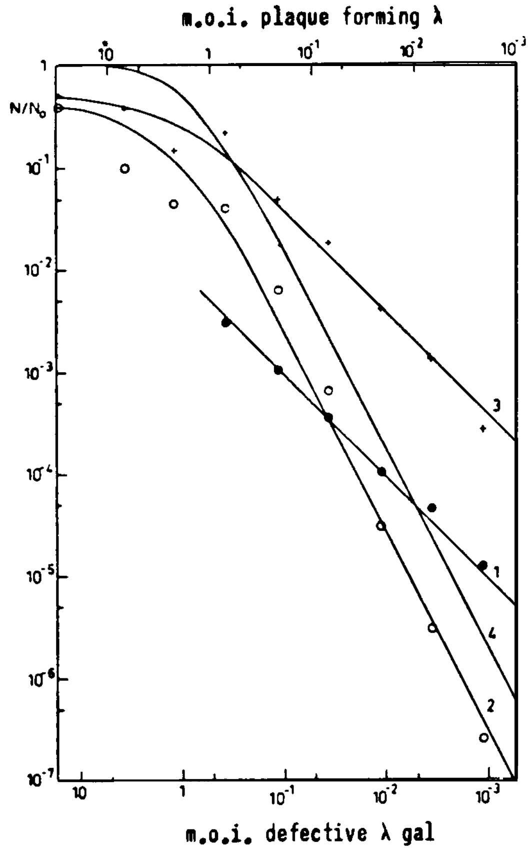

Fig. 1: Transduction and lysogenization of the *galT galK* strain W3350 of *E. coli* K12 by an HFT lysate.

The HFT (high frequency of transduction) lysate used was a phage stock composed of 4.4×10^{10} plaque forming λ phage particles and an estimated (from electron microscopical counts and physiological experiments) 2.3×10^{10} λgal phage particles, which were concluded from this and additional experiments to be defective in vegetative growth and partially affected in lysogenization. Aliquots of the host bacteria were infected at various multiplicities (m.o.i.) with the HFT lysate and then spread on EMB galactose indicator plates containing anti-h serum. Colonies grown after incubation were tested by replication for A-immunity and for the ability to produce plaque forming A upon induction.

N_o = number of recipient bacteria in infection mixture
N = number of recipient bacteria from the infection mixture found to be (I) Gal+, A-immune, not producing plaque forming A, hence carrying a λgal prophage; (2) Gal+, A-immune, producing plaque forming A and A gal (as verified with selected subclones), hence being doubly lysogenic for A and λgal; (3) Gal-, A-immune, producing plaque forming A, hence carrying a A prophage. (4) represents the calculated fraction of bacteria simultaneously infected with at least one A and one λgal (From Arber, 1958).

In the meantime, molecular geneticists have learned to isolate *in vivo* derivatives of A able to transduce practically any desired segment of the host chromosome, and this work has greatly facilitated detailed structural and functional studies of several selected *E. coli* genes. In addition, these

studies pointed the way to more recently undertaken approaches to produce in vitro recombinational hybrids between λ (or other vector DNA molecules) and DNA fragments from any chosen origin.

The studies of λ lysogeny and of the defective nature of λgal, which could be complemented by helper phage infection, also influenced work on animal and plant viruses. The knowledge acquired with λ was taken as a mode1 and this turned out to be extremely fruitful. We indeed know today that many situations similar to that of λ exist, where viruses are found integrated into the host chromosome and where viruses or fragments thereof can be shown to be defective but activatable by superinfection with exogenous helper virsus.

Let me now return to the process of integration and precise excision of the **A** prophage. As already stated, this site specific recombination was explained in a model devised by Campbell (1962). A long and careful study on this system has culminated a few years ago by its demonstration in vitro. Some of the few enzymes needed for the process are contributed by the A phage itself and others by the host bacteria (Nash, 1977). We also know the nucleotide sequences at which the interaction between the A genome and the bacterial chromosome occurs (Landy and Ross, 1977). These show homology over a stretch of 15 nucleotide pairs, but it has been shown that this length is not sufficient for efficient integration. Rather, the considerably longer, nonhomologous flanking segments play additional key roles in the interaction. This is the system of site specific recombination on which our knowledge is the most advanced.

The demonstration of recombinational events occurring independently of extended nucleotide homology, be they site specific or at random, brought up the question on possible limitations set by nature to such exchange which might be considered rather undesirable for the life of a cell.

Before two DNA molecules of different origin can interact with each other directly they must be brought into proximity, into the same compartment. Nature has certainly set up a number of mechanistic barriers such as membranes to limit free diffusion of genetic materials. On the other hand, we also know that a number of mechanisms exist with precisely allow the transfer of DNA from one cell to another, and that sometimes this exchange occurs between cells that are not directly related. May I recall that some bacteria1 conjugation plasmids have a relatively wide host range, and so do some bacteriophage strains able to transduce segments of the host chromosome, either by the already described specialized transduction, or also by the mechanism of general transduction, in which upon maturation the phage wrongly packages a segment of the host chromosome instead of its own phage genome. However, it is also clear that the host range is always limited by the need for specific cell surface interactions, and this seems to hold also for the penetration of free DNA into bacteria1 cells in the process known as transformation. On the other hand, bypass mechanisms have been demonstrated, e.g. that a phage genome is

transferable by bacterial conjugation (Jacob and Wollman, 1956) or that a conjugation plasmid is transduced by bacteriophage (Arber, 1960).

Sometimes the host range of a bacterial virus can become extended due to a mutation in one of the phage genes. In contrast to this situation, host-controlled variation (or modification, as it is now generally called) of bacteriophage, first described in the early 1950's (Luria and Human, 1952; Bertani and Weigle, 1953; Anderson and Felix, 1952; Ralston and Krueger, 1952) presented the puzzling situation that upon growth on different host strains, a virus could adapt to propagate on a new host without this ability being maintained upon backgrowth on the old host. Hence the adaption could not find its explanation by a mutation in the phage genome.

I became interested in these phenomena in 1960 and decided to look at the mechanisms of host-controlled modification of bacteriophage A. The two host strains of my choice were a pair of *E. coli* strains, K12 (shortly called K), and its PI lysogenic derivative K(P1). A few years before, Lederberg (1957) had shown that the Pl prophage determines a system of host-controlled modification. Restriction of λ·K (phage grown on K) by K(Pl) bacteria is quite strong: λ· K forms plaques on K(P1) host bacteria with an efficiency of 2×10^{-5} only (Fig. 2). In contrast, phage adapted to K(Pl) grows with full efficiency on both K and K(Pl). However, as is characteristic of host-controlled modification, when λ·K(P1) serves as inoculum for the growth of a multi-cycle stock of A on strain K, the resulting phage behaves exactly as the original λ·K. I wanted to know how fast this re-adaptation occurs. Therefore, I grew λ·K(P1) on strain K for just one lytic cycle, taking care to inactivate all non-adsorbed A with anti-A serum, which was then removed by washing. The result was striking. The one cycle progeny grew on the restrictive host K(Pl) with an efficiency of between 3×10^{-3} and 10^{-2} instead of 2×10^{-5}. Since the burst size per singly infected

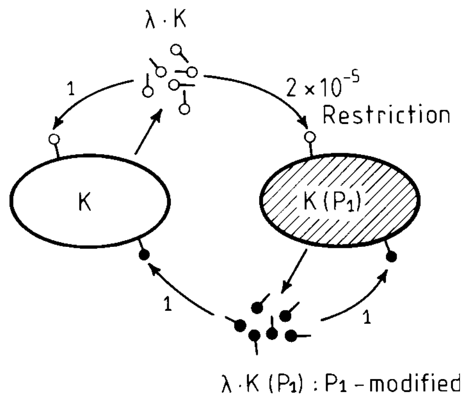

Fig 2: Pl-specific restriction and modification as detected by growth of bacteriophage λ.

Numbers give the efficiency of plating of phage variants λ·K and λ·K(Pl) on the hosts K and K(Pl) as indicated by the arrows.

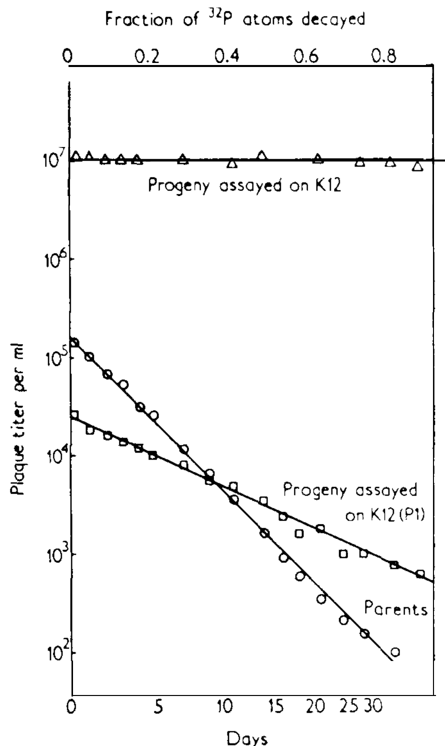

Fig. 3:

Joint transfer of parental DNA and parental PI-specific modification of heavily ^{32}P labeled λ·K(Pl) into the phage progeny produced after infection at a multiplicity of 0.006 phages per cell of the non-radioactive host strain K. See text for further explanations (From Arber and Dussoix, 1962).

host cell ranged between 100 and 200 A particles, this result suggested that about one progeny phage per cell had "inherited" the parental P1-specific modification (Arber and Dussoix, 1962; Arber, 1962). We were convinced that this was transferred from the infecting parental phage particle. But was it a diffusible internal phage protein or was it perhaps carried on the parental DNA molecule?

That the second possibility is the correct explanation became clear in the following experiment, which I would like to show, also for historical reasons. It had been demonstrated in the 1950's that DNA carrying radioisotopes loses its viability as a function of the radioactive decay (Hershey et al., 1951; Stent and Fuerst, 1955). Therefore, phage heavily loaded in its DNA with ^{32}P undergoes suicide upon storage. To my knowledge, the experiment shown in Figure 3 is the only important application of this rather special technique, which did allow us to trace parental DNA molecules in the course of replication at a time before density labeling methods had made their proof. A stock of heavily ^{32}P-labeled λ· K(Pl) was prepared and carefully purified. One aliquot was immediately used for one cycle of growth on non-radioactive K bacteria and the phage progeny was stored

and assayed from day to day. Another aliquot of the parental phage was directly stored and assayed from day to day. It is seen in Figure 3 that the viability of this parental phage disappeared exponentially as a function of the ^{32}P decay. In contrast, the bulk of the progeny phage grown on non-radioactive cells for one cycle was perfectly stable as revealed upon assay on K. However, those phages in the one cycle progeny able to grow on K(Pl) were inactivated, and their inactivation was about half as rapid as that of the parental phage (Arber and Dussoix, 1962). These results indicated that Pl-specific modification carried by the parental λ·K(P1) phage is transferred together with a parental DNA strand into the population of progeny phage particles. It must be noted that fragmentation of parental A DNA molecules can occur by recombination with progeny A DNA molecules in the course of the intracellular phage growth, but it affects at most half of the parental input. Such recombinants with less than semiconserved parental DNA would not grow on K(Pl), and their slow inactivation due to ^{32}P decay would not be detectable upon assay on K, since such phage particles represent a small minority of the progeny population.

About the same time Grete Kellenberger, who worked in the same laboratory, and Daisy Dussoix, a Ph. D. student, studied the breakdown of DNA from irradiated phage λ upon infection of normal host bacteria. We wondered if the mechanisms of Pl-specific restriction and of inactivation of phage caused by irradiation had anything in common. For this reason the fate of A DNA is restrictive host bacteria was investigated, and we could demonstrate that in the infection of K(Pl) bacteria with λ·K phage an important fraction of the phage DNA was rapidly degraded (Dussoix and Arber, 1962). No DNA breakdown was seen in the λ· K-infected K bacteria.

The implication of these early findings, that host-controlled modification affected DNA, although the phenomenon could not be explained as a mutation, found rapidly additional support. We also realised that the phenomenon does not directly depend on phage λ used in the studies and that it affects any other DNA in the same way as A DNA, e.g. bacterial DNA in conjugation (Arber, 1962). Hence restriction and modification (R-M) systems can be looked at as serving as defence mechanisms against the uptake of foreign DNA and restriction to be brought by nucleolytic activity.

It took us a while to find out how bacteria can protect their own DNA against their restriction nucleases. They do so by postreplicative nucleotide methylation at the sites serving the R-M systems for specificity recognition (Arber, 1965; Smith et al., 1972; Kühnlein and Arber, 1972).

Interestingly, the R-M systems *Eco*P1, *Eco*K and *Eco*B with which the fundamental genetic and physiological experiments were carried out do not cleave the DNA precisely at the sites used for recognition (Horiuchi and Zinder, 1972). This points to rather complex molecular mechanisms by which these enzymes act. Careful investigations have already revealed important aspects of them (Arber et al., 1975; Yuan et al., 1975; Bickle et

al., 1978), so that these systems can serve as models in investigations of other nucleic acid protein interactions, particularly those showing regional rather than site specificity. I think in particular at some as yet poorly understood recombination phenomena pointing to regionally increased probability of interchange.

Other restriction enzymes, as is now well known, do cleave unmodified DNA at the recognition site, which is specific for each particular R-M system. I think that my colleagues Hamilton Smith and Daniel Nathans will discuss aspects of the mechanisms of these enzymes and of their application to studies of structure and function of DNA. Let me therefore just mention what is relevant with regard to *in vivo* genetic exchange. Since restriction enzymes have been widely used in *in vitro* recombination of DNA molecules it is of interest to see that these enzymes can also trigger recombination *in vivo* (Chang and Cohen, 1977). Hence, as in other biological activities with ability to catalyze antagonistic reactions, the restriction enzymes in question can both inhibit genetic exchange as well as promote it to some degree. This recombination does of course not depend on major nucleotide homologies on the interacting DNA molecules, but only on the existence of recognition sites for the enzymes determined by 4 to 6 nucleotide pairs in general.

The discovery of still another type of genetic exchange not based on nucleotide homology has also its roots in work with phage λ. Peter Starlinger was among those fascinated by the explanation of how λgal phages were formed. In the early 1960's he and his collaborators had fruitfully extended the knowledge on the randomness of the illegitimate recombination by genetically determining the endpoints of the bacterial material picked up by λgal. This formed a part of their studies on the structure and function of the galactose operon of *E. coli.* In the course of their work they encountered unorthodox mutations with strongly polar effects and several other unexpected properties. Further investigations of the nature of these mutations, as well as of similar mutations isolated in other laboratories, finally revealed the existence of what is now known as Insertion Sequences or IS elements (Starlinger and Saedler, 1976; Bukhari et al., 1977).

It would be premature to list general properties of IS elements and related structural entities. It is clear, however, that these elements of the size of about 600 to 2000, or more, nucleotide pairs can be found in *E. coli* and in other bacteria in one or more copies carried at a number of different chromosomal sites. Spontaneously, such an IS element can show up at a site not previously occupied by it. This event is called transposition, although it remains unclear if the element really jumps from one location on the chromosome to another, or if a resident IS element prepares a new copy in view of its integration at a new site. On the other hand, it is clear that IS elements generally can indeed excise, either precisely or imprecisely, from a given site. Another often encountered property of IS elements is their ability to form deletions starting at one of the ends of the IS element

and extending to a perhaps randomly chosen site at a distance of sometimes several genes. All these events are rare indeed, but occur at measurable frequencies of perhaps 10^{-4} to 10^{-8} per cell division, depending on the system studied. They must be enzymatically determined, and it is likely that the rate limiting factors are usually repressed. Presumably for this reason, no enzymological *in vitro* studies of these mechanisms have yet been successful. It is still a guess that one or several of the genes determining the activities of IS elements are located on the IS element itself, which is also supposed to have specific sites involved in the events of transposition, excision and deletion formation. Some IS elements have been shown to contain regulatory signals for gene expression.

Most of the IS elements described so far in the literature were chance isolates, and it remains largely unknown how many different IS elements are carried e.g. in *E. coli* K12, nor does one yet have good ideas on the host range of particular IS elements. We have started to look for answers to these questions by the use of a large plasmid, the bacteriophage Pl prophage, to trap transposing IS elements inside the *E. coli* cell. Interestingly, an important proportion of spontaneous P 1 prophage mutations affecting the functions of vegetative phage growth is explained by the incorporation of IS elements, which must originate from the host chromosome. On the other hand, several IS elements were also found by chance carried in genomes of Pl derivatives not affected in their functions of vegetative growth. Preliminary studies indicate that many of the IS elements isolated are independent of each other. This should allow us to establish a library of transposable IS elements isolated from host strains of bacteriophage PI. Hybridisation studies with these IS elements and DNA from various origin is then expected to shed light on the question of the host range of particular IS elements (Arber et al., 1979).

IS elements have also been shown to mediate the exchange of more extended DNA segments. Transposons are DNA segments flanked by identical IS elements or at least repeated sequences. One of the important features of a transposon is that it can insert as a unit into another chromosome. For example, an r-determinant element of 23 kb length, carrying the genes for resistance to several antibiotics and originally identified as a constituant of R plasmids, has been shown to transpose into phage Pl, from this into the *E. coli* chromosome and from the chromosome into another bacteriophage genome (Arber et al., 1979). This clearly shows that under natural conditions relatively long DNA segments can translocate onto a transferable vector DNA molecule, such as a viral genome or a conjugative plasmid. And the same element at some later time in another host cell can transpose into a cellular chromosome. In principle, there is no limit set for genes to be picked up at one time or another on a transposable element, since the elements flanking a transposon can also transpose independently and thus by chance give rise to the formation of new transposons.

IS elements and related repeated sequences also give rise to cointegra-

tion of two DNA molecules, as well as to the dissociation of a single DNA molecule into two. Chromosomal integration and excision of F and R plasmids is just one example. Finally a few additional mechanisms contributing to genetic rearrangement and diversity should also be mentioned: gene inversion, gene amplification and the formation of short partial duplications. These mechanisms seem also to be driven by IS elements flanking the genes involved.

In this lecture I have tried to show that the deeper we penetrate in the studies of genetic exchange the more we discover a multitude of mechanisms either acting as promotors of exchange or acting to set limits to it, and some do both. On purpose I discussed only procaryotes and did so largely by taking examples from *E. coli* and its phages and plasmids.

I am aware and puzzled by the roles that site specific exchanges may play in the ontogeny of higher organisms and at the level of the RNA in gene expression.

I gave some thought on the possible reasons why *E. coli* bacteria might have set up such a multitude of systems involved in the genetic exchange which for some reasons must be vital for them. I must confess that I did not find out why, besides trivial answers such as "serving in repair processes" or "evolutionary driving forces" for the promoting activities, and "species isolation" or "genetic stability" for the activities keeping genetic exchange within limits. More intensive research is needed to understand the apparent complexity of nature. But one important notion already obtained might be good to keep in mind: in spite of possessing a multitude of natural mechanisms to promote exchange between genetic materials of unrelated origin, E. *coli* and other living organisms have succeeded to accomplish a relatively high overall stability in their genetic make-up.

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