

A MODEL FOR ADDITIVE CROSS-OVER UNITS IN
GENETIC LINKAGE ANALYSIS

BU-164-M

D. S. Robson

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Abstract

If the number of cross-overs occurring between two loci is a Poisson random variable with mean λ then the probability of an odd number of cross-overs is $p = (1 - e^{-2\lambda})/2$. Cross-over units measured on the scale of $\lambda = -[\log(1-2p)]/2$ rather than on the p -scale would therefore be additive.

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A parent carrying the gene arrangement $\frac{AB}{ab}$ on a particular chromosome will transmit AB and ab gametes with equal probability, say $(1-p)/2$, while gametes of type Ab and aB will each be transmitted with probability $p/2$. The fraction p therefore denotes the probability that in the process of gamete production an odd number of chromosomal cross-over will occur between these two loci. It is an empirical fact that as the distance between loci increases, the probability p approaches $1/2$, in which case the two loci effectively segregate independently.

The fraction p is employed in linkage analysis as a measure of the "cross-over distance" between loci; thus, if gametes in the repulsion phase (Ab or aB) are produced in $100p_{AB}$ percent of the cases then the A and B loci are said to lie $100p_{AB}$ cross-over units apart. If a third locus appears with the configuration $\frac{ABC}{abc}$, however, then $p_{AC} \neq p_{AB} + p_{BC}$, and cross-over units so defined are not additive.

If the number of cross-overs occurring between two loci is a Poisson random variable with mean λ then p , the probability of an odd number of cross-overs, is

$$p = \frac{1 - e^{-2\lambda}}{2} .$$

This result may be obtained by noting from the relation

$$p = e^{-\lambda} \left(\lambda + \frac{\lambda^3}{3!} + \frac{\lambda^5}{5!} + \frac{\lambda^7}{7!} + \dots \right)$$

that as a function of λ , p satisfies the differential equation

$$\frac{dp}{d\lambda} = e^{-\lambda} \left(1 + \frac{\lambda^2}{2!} + \frac{\lambda^4}{4!} + \dots\right) - e^{-\lambda} \left(\lambda + \frac{\lambda^3}{3!} + \frac{\lambda^5}{5!} + \dots\right)$$

or

$$\frac{dp}{d\lambda} = 1 - 2p$$

The boundary condition that $p = 0$ when $\lambda = 0$ then determines the solution indicated above. As λ increases, p rapidly approaches the limiting value of $1/2$; for an average of $\lambda = 1$ cross-over between two loci the value of p is already .432, and if $\lambda = 2$ then $p = .491$.

If, as would be implied by the Poisson model, cross-overs between the A- and B-locus occur independently of those between the B- and C-locus in the configuration $\frac{ABC}{abc}$ then the corresponding Poisson parameters λ_{AB} and λ_{BC} are additive; that is, $\lambda_{AC} = \lambda_{AB} + \lambda_{BC}$. For chromosomal mapping purposes, therefore, the transformation from p to

$$\lambda = \log_e \frac{1}{\sqrt{1-2p}} = -\frac{1}{2} \log_e (1-2p)$$

would provide a much more convenient scale of "cross-over distance" and would have the further advantage of being simply interpreted as the mean number of cross-overs.

As is characteristic of classical linkage analysis, statistical estimation of λ (or p) would approach the impossible as p approaches $1/2$. Since the estimate of p is a binomial variable, however, then for large samples the

estimate of λ would be approximately log-normally distributed with mean λ and variance $16p(1-p)/n(1-2p)^2$. For closely linked loci this variance would become simply $16p/n$.

A check on the validity of this model can be readily made by checking the additivity of λ from available data. Sample size, however, must be truly large in order to detect departures from this model. Three examples (1) involving triple heterozygotes have been checked.

Gamete numbers			
ABC or abc	Abc or aBC	ABc or abC	AbC or aBc
5246	229	1227	6
3344	245	1504	88
4287	721	2403	235

Estimates of λ		
$\hat{\lambda}_{AB} \pm 2\hat{\sigma}_{\lambda_{AB}}$	$\hat{\lambda}_{Bc} \pm 2\hat{\sigma}_{\lambda_{Bc}}$	$\hat{\lambda}_{Ac} \pm 2\hat{\sigma}_{\lambda_{Ac}}$
.053 \pm .025	.221 \pm .071	.275 \pm .072
.069 \pm .031	.477 \pm .133	.562 \pm .162
.144 \pm .040	.586 \pm .140	.849 \pm .246

none of which contradict the model $\lambda_{AB} + \lambda_{Bc} = \lambda_{Ac}$.

Reference

1. Sansome and Philp, Recent Advances in Plant Genetics. P. Blakiston's Son & Co. Inc., Philadelphia, 1939, p. 93.