A GENETIC AND BIOMETRICAL STUDY OF GROWTH IN CHICKENS

A Thesis

Submitted to the Faculty

of

Purdue University

by

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In Partial Fulfillment of the

Requirements for the Degree

of

Doctor of Philosophy

June 1969

DEDICATION

TO MY PARENTS AND ALFRED

ACKNOWLEDGMENTS

A wise man noted that giving birth to an idea is one thing but raising it to maturity is quite another. No idea can be raised to maturity completely by one person. It took the effort, in one way or another, and cooperation of many people to make this thesis possible. Therefore:

I sincerely want to express my appreciation to my major professor, Dr. B. B. Bohren, not only for his intellectual guidance and encouragement, but also for the continuing patience he showed me throughout my developing years as his student;

I would like to thank Dr. V. L. Anderson for his consultations in statistical methods and inspiration as a teacher, Drs. A. E. Bell and M. Stob for their willingness to serve on my committee, Dr. J. R. Carson for his cooperation in providing the help of Mr. Harold Vice and Mr. Kenny Hurt in collecting the data as well as providing the facilities of the Purdue University Poultry Center Farm, Mr. ''Dutch'' Fleming for his assistance in the collection of the data, Miss Peggy Fahl for always doing more than was asked of her in typing the preliminary drafts of this thesis, and also Mrs. Myrna Harrison and Mrs. Dorothy Penner for typing the final product;

I want to extend a special appreciation to Dr. T. B. Kinney, Jr. who always gave, unselfishly, both of his time and effort to me;

I am grateful for the financial support given to me by the Department of Animal Sciences from 1965 to 1967 and by an NIH Biometry Training Grant (GM 00024) from 1967 through 1969;

Finally, I want to thank my parents and brother, Alfred, for their constant concern for my needs, their awareness of my trials and difficulties and their interest in my well being and peace of mind. These people, and others, have helped me reach this point in my life.

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ABSTRACT

Grossman, Michael. Ph.D., Purdue University, June 1969. A Genetic and Biometrical Study of Growth in Chickens. Major Professor: B.B. Bohren.

The purpose of the research reported in the first chapter was to study genetic and biometrical relations among body weights and gains and derive theoretical expectations for correlations between consecutive body weights, gains, and between weights and gains. All analyses were based on measurements taken on weekly body weights of 909 chickens of both sexes from two random mating control lines, Rhode Island Red (RIR) and White Leghorn (WL), from hatching to 45 weeks of age.

A direct relationship between the mean and variance was observed for weights. Phenotypic and genetic coefficients of variation increased until about six weeks, declined and leveled off at about 12 and 10 percent, respectively.

In the RIR females the sire components of variance were negative from one to eight weeks. A similar phenomenon existed during the later ages of the WL females. A possible explanation in terms of a negative estimate of the phenotypic correlation among half sibs was proposed. The negative estimate was probably brought about by competition for food and social interaction among half sibs.

The correlations between consecutive weights increased until seven weeks, remaining at almost one thereafter. The correlations between hatching and successive weights decreased until three weeks, remaining low thereafter. The correlations between final and preceding weights began low and increased over time. These correlations represent a part-whole relationship.

The means and variances of gains did not vary together as with weights. Heritabilities had a downward trend indicating increasing environmental variation especially after 31 weeks. Average heritabilities and genetic correlations of gains were low. Correlations between consecutive gains went from positive to negative. Negative correlations between weights and gains implied compensatory growth but not necessarily a reduction in the variance of weights.

The purpose of the research reported in the second chapter was to determine and study parameters of a mathematical function best fitting the weight curve of the four populations. Among these parameters was the intrinsic growth rate constant expressing the rate of gain as a function of weight at a specific time and gain to be made. It was hypothesized that the rate constant was heritable.

The logistic function was chosen from among those formulae expressing rate of gain as a function of the rate constant. The logistic parameters were estimated from mean weights by nonlinear regression and order statistics. Order statistics was also used to estimate the parameters from individual weights. Four parameters were estimated: initial and maximum weights, the intrinsic growth rate constant and age at the inflection point.

Males had a larger intrinsic growth rate than females of the same line. The RIR line had a larger rate constant than the WL line, within a sex. The age at the inflection point was larger (smaller) for males (females) in the RIR than males (females) in the WL line.

Estimates of heritabilities for the rate constant and age at inflection point indicated that the variance among values of both parameters was not due to heritable differences. Thus, if selection were applied to either or both traits, a change in the genetic mean would not be expected. No genetic correlations were evident among the logistic parameters.

It was concluded that any attempt to genetically change the shape of the growth curve of these chickens, by selecting for high growth rate constant or low age at inflection point, would probably not be successful. If selection were practiced, however, a correlated genetic change in the initial or maximum weight would not be expected.

CHAPTER I. BIOMETRICAL RELATIONSHIPS AMONG BODY WEIGHTS AND GAINS

LITERATURE REVIEW

A considerable amount of research has been done on different body measurements of chickens. Interest has usually been focused on the change of body weight over several generations; the long range goal being improvement through selection. Besides body weights at different ages, gains in weight between these ages have also been the object of much research.

Essential in the improvement of a trait through selection is the accuracy with which the heredity of an individual, for that trait, is predicted by the observed measurement. The accuracy may be thought of as a quantity measured by the heritability (Lush, 1945). Kinney (1969) has summarized most of the estimates of the heritability of body weights and gains available in the literature. His comprehensive review of many traits of the chicken shows that body weights and gains have been studied only at a few specific times in the chicken's life over several generations. This information has usually been utilized in selection programs for weight at a certain age. It appears then that no work has been done on the relationship among and within weekly body weights and weekly gains.

Therefore, it was the purpose of this research to study the heritabilities of weekly body weights and gains over a period of about one year. In addition, the theoretical correlations between consecutive weights, consecutive gains, weights and subsequent gains, as well as gains and subsequent weights have been derived under varying assumptions. The theoretical results have been compared to empirical results.

MATERIALS AND METHODS

Description of the Populations

A total of 4752 eggs, collected during a three week period, was obtained through the cooperation of Dr. T. B. Kinney, Jr. and the North Central Regional (NCR) Poultry Breeding Laboratory at Purdue University. Of these eggs, 2123 were sampled from the White Leghorn Cornell (WL) Control line and 2629 sampled from the Rhode Island Red (RIR) Control line. Both lines were randombred and maintained by a hierarchical mating structure according to the procedures described by King et al. (1959).

All eggs, identified by sire and dam, were placed at random into two Single Stage 252 Jamesway incubators, on 23 June 1966, operating at normal levels of temperature and relative humidity. On the 18th day, they were transferred to pedigree baskets, without being candled, and placed into hatchers from which they were removed on the 22nd day, 15 July. The chicks were sexed and dam families with four or more progeny were selected, wing band identified according to sire and dam, and weighed. The males were decombed and all birds were kept in chick boxes overnight. The next day the chicks were assigned at random to four pens, one for each line and sex combination (or four populations). A restriction on randomization was that the lines alternate in order to facilitate recognizing a chick in the wrong pen, especially during the early stages of the experiment. The pens were 7.6 by 9.1 meters or about 70 square meters (25 by 30 feet or 750 square feet).

At one week of age, only those dam families with five or more and six or more progeny of a sex were saved in the RIR and WL lines, respectively. It was assumed that no correlation existed between the measured trait and family size. This method of choosing the population inadvertantly led to several sire families with only one dam represented.

Starting at one week of age there were 302 males and 320 females in the RIR line and 350 males and 351 females in the WL line. At the conclusion of the experiment, 26 May 1967, there were 225 males and 281 females in the RIR line and 164 males and 239 females in the WL line. Tables A1-A4 (Appendix A) present the family structure of each population at the conclusion of the experiment.

Description of the Trait

The primary characteristic measured was individual weekly body weight from hatching to 45 weeks of age. Weights were taken to the nearest gram on a Toledo Fan Scale, Model 4020. There was no order in which the birds within a pen were weighed each week. However, the order of the pens was kept constant after initially being chosen at random with the restriction that the females be weighed in the afternoon. This restriction was imposed because it was felt that when the females became sexually mature most of them would lay their eggs in the morning or early afternoon and their body weight in the afternoon would not be biased by the weight of their egg in the oviduct (Lowe, et al. 1968).

The secondary characteristic studied in this phase of the experiment was the change in the individual's body weight. This trait, gain in weekly body weight, was defined as the difference between two consecutive weekly body weights on the same individual.

Description of the Environment

In an attempt to keep the environment as constant as possible throughout the experiment, all chicks were brooded under infra-red heat lamps and were maintained in the same pens, without heat, on a litter of corn cobs. It is well known that high temperature inhibits growth of chickens, especially during the growing season. If the chicks were hatched in early spring, they would be about 20 weeks of age during July and the seasonally warm temperatures here during July and August might retard their growth. Therefore, the chicks were hatched in July to take advantage of the warm temperatures during the period of their life when they required supplemental heat. Both feed and water were given ad libitum.

In the late afternoon of the day prior to weighing, the feed was removed from each pen so that the weight of the bird would not be biased by the feed consumed immediately prior to weighing. As soon as the weights in each pen were taken, the feed was returned. There were approximately 20 linear meters (64 linear feet) of feed space throughout the experiment in each pen. From 1 to 140 days of age they were fed Purdue Developer Ration. The ration was then supplemented with oyster shells given at free choice for 18 days. The oyster shells also were removed from the pen prior to weighing except at 21 weeks when the shells were accidently left in the pens. This was considered to have a negligible effect. Beginning at 159 days of age both males and females were fed the Purdue Layer Ration. The components of both rations are presented in Table A5.

At about two weeks of age, all chicks were water vaccinated against Newcastle disease and at about 6 and 20 weeks of age against both

Newcastle disease and bronchitis. All birds were debeaked between 10 and 11 weeks of age and were exposed only to natural light, except during the hours that they were being weighed when artificial light was used also. They were periodically resexed up to 22 weeks of age and placed into the appropriate pens. Grit was given at various times up to about 15 weeks of age.

Description of Statistical Procedures

Means, Standard Deviations and Coefficients of Variation

Only those progeny which survived to 45 weeks of age were included in the statistical analyses. The reason for this is that individuals that died during the experiment were probably not growing to their full potential prior to death and information from them probably would have biased the results. The means and variances of individually observed body weights and gains were calculated weekly for the survivors in the four populations. In the case of a trait where the mean and variance (or standard deviation) are related, a parameter is needed so that the variance is standardized by the mean. The coefficient of variation expresses the standard deviation as a fraction or percentage of the mean, i.e. $\sigma(100)/\overline{X}$ (Snedecor and Cochran, 1967). Body weight is a trait in which the mean and standard deviation vary together. Therefore, extimates of both the phenotypic and ''genetic'' coefficients of variation were obtained for weekly body weights in each population.

The phenotypic coefficient of variation is based on the phenotypic mean and standard deviation of the four sampled populations. The phenotypic variance is of a finite population. The genetic coefficient of variation is a ratio of the square root of the additive genetic variance to the genotypic mean. Since the numbers in this experiment were relatively large for this purpose, it was considered valid to assume that the environmental mean was zero. Thus, the genotypic mean was estimated by the phenotypic mean.

Heritability of Weekly Body Weights

Heritability, which measures the degree to which an individual's phenotype is related to its genotype, is the ratio of the additive genetic variance to the total phenotypic variance. It is an essential parameter in the prediction of progress due to selection for a trait.

Heritability estimates based on paternal and maternal half sib and full sib correlations (Falconer, 1960) were calculated from weekly nested analyses of variance on weekly body weight data. The assumed statistical model for the analysis was:

$$W_{tijk} = \mu_t + S_{ti} + D_{tij} + \epsilon_{tijk},$$

where:

W_{tijk} = the weight of the kth individual from the jth dam mated to ith sire at week $\underline{t}$, $t = 0, \ldots, 45$

μ_t = the theoretical overall mean at week $\underline{t}$

S_{ti} = the differential effect of the ith sire at week $\underline{t}$, $i = 1, \ldots, s$

D_{tij} = the differential effect of the jth dam mated to the ith sire at week $\underline{t}$, $j = 1, \ldots, d_i$ and

ϵ_{tijk} = the random error, $k = 1, \ldots, n_{ij}$ progeny/dam/sire.

Furthermore, for week $\underline{t}$:

$\sum_j n_{ij} = n_{i.}$ = the number of progeny/sire

$\sum\sum_{ij} n_{ij} = N$ = total number of progeny.

The following assumptions are required:

1) $S_{ti} \sim NID(0, \sigma^2_{S_t})$, $D_{tij} \sim NID(0, \sigma^2_{D_t})$, $\epsilon_{tijk} \sim NID(0, \sigma^2_t)$.

2) All effects are mutually uncorrelated for fixed $\underline{t}$.

3) There are no interactions between sires and dams. This assumption is necessary since the dam component was assumed not to include dominance variance.

The form of the weekly analysis of variance is presented in Table 1.1.

The heritability estimates for week $\underline{t}$ were calculated as:

$$h^2_{S_t} = \frac{4\sigma^2_{S_t}}{\sigma^2_{P_t}}, \text{ when based on the sire component,}$$

$$h^2_{D_t} = \frac{4\sigma^2_{D_t}}{\sigma^2_{P_t}}, \text{ when based on the dam component and,}$$

$$h^2_{S+D_t} = \frac{2(\sigma^2_{S_t} + \sigma^2_{D_t})}{\sigma^2_{P_t}}, \text{ when based on both sire and dam components,}$$

where $\sigma^2_{P_t}$ is the total phenotypic variance in week $\underline{t}$ (see King and Henderson, 1954 for the unequal subclass number case).

Standard errors for the heritability estimates were calculated using the procedure suggested by Osborne and Paterson (1952). Dickerson (1963) presents the method for the case of unequal subclass numbers.

Table 1.1. The Form of the Weekly Analyses of Variance

Source	d.f.	EMS*
Sires (S)	$s - 1$	$\sigma^2_t + k_2\,\sigma^2_{D_t} + k_3\,\sigma^2_{S_t}$
Dams (D)/S	$\sum_i (d_i - 1)$	$\sigma^2_t + k_1\,\sigma^2_{D_t}$
Progeny/D/S	$\sum_{ij}\sum (n_{ij} - 1)$	σ^2_t
Total	$N - 1$	

*Coefficients of variance components:

$$k_1 = \frac{1}{\sum_i (d_i - 1)}\left[N - \frac{\sum_{ij}\sum n^2_{ij}}{N}\right]$$

$$k_2 = \frac{1}{s-1}\left[\sum_i\left(\frac{\sum_j n^2_{ij}}{n_{i.}}\right) - \frac{\sum_{ij}\sum n^2_{ij}}{N}\right]$$

$$k_3 = \frac{1}{s-1}\left[N - \frac{\sum_i n^2_{i.}}{N}\right]$$

Interpretation of Sire and Dam Components of Variance. To obtain a better understanding of heritability, one must examine the component terms of the parameter. The sire and dam components of variance can be interpreted in terms of phenotypic correlations (Lowry, 1955). For some week t,

$$\sigma^2_{S_t} = \rho_{HS_t} \sigma^2_{P_t}$$

$$\sigma^2_{D_t} = (\rho_{FS_t} - \rho_{HS_t}) \sigma^2_{P_t},$$

where: ρ_{FS_t} and ρ_{HS_t} are the phenotypic intraclass correlations for full and paternal half sibs, respectively and $(\rho_{FS_t} - \rho_{HS_t})$ is the maternal half sib correlation.

Using the approach of Snedecor and Cochran (1967, p. 294), the expected value of the sire mean square must be greater than or equal to zero, and therefore the lower bound for ρ_{HS} is found to be:

$$\rho_{HS} \geq \frac{1-(n-1)\ \rho_{FS}}{n(d-1)}$$

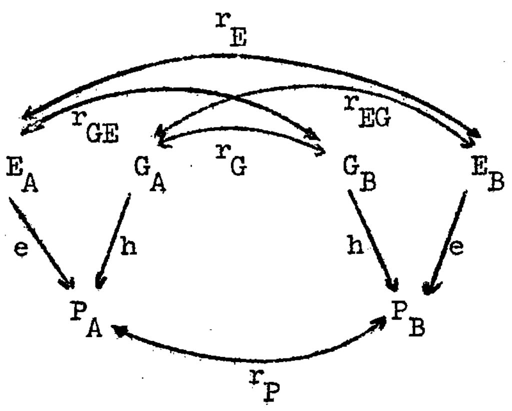
where n is the number of full sibs per dam, and d the number of dams mated to each sire in the equal number case. The half sib correlation has a lower limit which is negative when,

$$\rho_{FS} > \frac{1}{(n-1)} .$$

Thus, under the above condition on the full sib correlation, a negative estimate of the half sib phenotypic correlation could give an estimate of the sire component which is truly negative. The question then is why a negative correlation estimate, for example ρ_{HS}, the correlation among weights within a half sib family, should be a real phenomenon, based on an assumed model, and not an accident of sampling.

Since the true correlation among half sibs can never be negative (it is an intraclass correlation) one must admit that the assumed statistical model does not explain the biological phenomenon. Given the assumed model, however, Snedecor and Cochran suggest that a possible reason for a negative estimate of correlation is competition for an insufficient supply of food. In that case, the more aggressive animals may force the timid animals away from the food and eat more themselves. The composition of the phenotypic correlation among half sibs will be explored further to determine how competition could make the estimate of the half sib correlation negative.

The Phenotypic Correlation Among Half Sibs. The phenotypic correlation, in general, may be expressed in terms of genetic, environmental and genotype by environment correlations. This can be seen from the following path diagram:



where: r_P = phenotypic correlation between individuals α and β for traits P_A and P_B

r_G = genetic correlation between individuals α and β for traits P_A and P_B

r_E = environmental correlation between individuals α and β for traits P_A and P_B

r_{EG} = correlation between environmental effect on P_A and genotypic effect on P_B

r_{GE} = correlation between genotypic effect on P_A and environmental effect on P_B

h = coefficient of path from the genotype (G) to the phenotype (P_A or P_B)

e = coefficient of path from the environment (E) to the phenotype (P_A or P_B)

The explanation of the coefficients <u>e</u> and <u>h</u>, known as path coefficients, may be found in the works of Wright (1921, 1934 and more recently 1968). In particular, <u>h</u> may be defined as the positive square root of heritability, $\underline{h}^2$.

Specifically, it can be shown that in the case of body weight measured on two half sibs, α and β, at a given age, the phenotypic correlation between the sibs is:

$$\rho_{HS} = h^2(r_G) + e^2(r_E) + he(r_{GE}) + he(r_{EG})$$

where $r_G = \frac{1}{4}$, assuming no dominance variance (Li, 1968) and no inbreeding. Since <u>h</u> and <u>e</u> are both positive values, a negative value of

ρ_{HS} must come about because either r_E, r_{GE}, or r_{EG} (or any combination) is negative.

It is well known that the maternal (environmental) influences in the chick are great, especially in its early life. The size of the chick is directly proportional to the size of the egg which the hen lays. Take for example two paternal half sibs, α and β, and look at their phenotypes P_A and P_B. Assume body weight of α, P_A, is larger than the body weight of β, P_B, for both genetic and maternal reasons. Thus, we shall assign a plus (+) value to α's genotypic and environmental effects (or deviations), G_A and E_A. We shall assign a minus (-) value to β's genotypic and environmental deviations, G_B and E_B. Consequently, relative to α's environmental deviation, β's environmental deviation is negative. Also, relative to α's genotypic deviation, β's environmental deviation is negative. Similarly, G_B is negative relative to E_A. This relationship is manifested in competition for food. The individual α, being larger, and perhaps more aggressive, than β will compete more favorably for food and prevent β from eating. Thus, relative to E_A, both G_B and E_B are negative and relative to E_B both G_A and E_A are negative. It can be seen, therefore, that due to a temporary maternal influence, a negative correlation between paternal half sibs may be generated.

This is not to say that competition is the only influence associated with a negative phenotypic correlation. Nor can it be said that the differential maternal effect actually did manifest itself in competition for food. The maternal effect could not be tested since it was not included in the assumed model. Further study in this area should be most interesting.

Heritability of Weekly Gains in Body Weight

Heritability estimates of weekly gains in body weight based on paternal and maternal half sib as well as full sib correlations were calculated from weekly nested analyses of variance. The assumed statistical model was:

$$G_{tijk} = \mu_t + S_{ti} + D_{tij} + \epsilon_{tijk}$$

where: G_{tijk} = the gain between weeks <u>t</u> and <u>t+1</u> of the kth individual from the jth dam mated to the ith sire, $t=0,\ldots, 44$.

The assumptions are as presented in the previous section. Table 1.1 shows the form of the weekly analyses of variance. Standard errors were estimated as before.

Analysis of Variance of Weekly Gains in Body Weight

In order to further study the relationship among the weekly gains in body weights, an analysis of variance was performed, for each population, over all weekly gains. An analysis of variance for body weights was precluded because of the high correlation between the errors of consecutive weights and the increasing variance of body weights over time. Based on the empirical observations indicating a lack of consistently high correlations between consecutive gains and a fluctuating variance of gains over time, it was felt that an analysis on gains would be valid.

Therefore, an analysis of variance was performed on weekly gains in body weight for all populations. The assumed model for the variable to be analyzed was:

$$G_{ijkt} = \mu + S_i + D_{ij} + P_{ijk} + W_t + WS_{it} + WD_{ijt} + WP_{ijkt} + \epsilon_{ijkt}$$

where: μ = the true mean

S_i = the differential effect of the ith sire, $i=1,\ldots, s$

D_{ij} = the differential effect of the jth dam within the ith sire, $j=1,\ldots, d_i$

P_{ijk} = the differential effect of the kth full sib progeny from the jth dam within the ith sire, $k=1,\ldots, n_{ij}$ progeny/dam/sire

W_t = the differential effect of the tth week of age, $t=0,\ldots,44$

WS_{it} = the differential effect of the interaction of the tth week with the ith sire

WD_{ijt} = the differential effect of the interaction of the tth week with the jth dam mated to the ith sire

WP_{ijkt} = the differential effect of the interaction of the tth week with the kth progeny of the jth dam mated to the ith sire

ϵ_{ijkt} = residual

Furthermore:

$\sum_j n_{ij} = n_{i.}$ = number of progeny/sire

$\sum_i n_{i.} = n$ = number of progeny/week

$\sum_i d_i = d$ = total number of dams

$w = 45$ = number of weeks

nw = total number of observations.

The following assumptions are necessary:

1) $S_i \sim NID(0,\sigma_S^2)$, $D_{ij} \sim NID(0,\sigma_D^2)$, $P_{ijk} \sim NID(0,\sigma_P^2)$

and $\epsilon_{ijkt} \sim NID(0,\sigma^2)$

$$\sum_t W_t = \sum_t WS_{it} = \sum_t WD_{ijt} = \sum_t WP_{ijkt} = 0$$

$$\phi(W) = \frac{\sum_t W_t^2}{w-1}, \quad \sigma_{WS}^2 = \frac{\sum_t E(WS_{it})^2}{w-1}$$

$$\sigma_{WD}^2 = \frac{\sum_t E(WD_{ijt})^2}{w-1}, \quad \sigma_{WP}^2 = \frac{\sum_t E(WP_{ijkt})^2}{w-1}$$

2) All effects are mutually uncorrelated for fixed weeks (t).

3) There are no interactions between sires and dams. Thus, the dam component of variance estimates one-fourth of the additive genetic variance.

Since the same individuals were measured each week, the progeny are nested within matings but are factorial to weeks. Thus, we have a nested factorial experiment in a split plot design. Many people consider the nested factorial as a type of split plot design. In its use here, however, nested factorial experiment refers to how the levels of the factors (sires, dams, progeny and weeks) were combined, while split plot design refers to a restriction on the randomization of the observations (Hicks, 1964). Sire, dam and progeny effects were considered random, but the week effect was considered as fixed; accounting for the mixed model. The form of the analysis of variance for gain in body weight over weeks is presented in Table 1.2.

Table 1.2. The Form of the Analysis of Variance for Gains in Weekly Body Weight.

Source	d.f.	EMS*
Sires (S)	s-1	$\sigma^2 + w\sigma_P^2 + k_7\sigma_D^2 + k_8\sigma_S^2$
Dams (D)/S	d-s	$\sigma^2 + w\sigma_P^2 + k_6\sigma_D^2$
Progeny (P)/D/S	n-d	$\sigma^2 + w\sigma_P^2$
Weeks (W)	w-1	$\sigma^2 + \sigma_{WP}^2 + k_4\sigma_{WD}^2 + k_5\sigma_{WS}^2 + n\phi(W)$
W x S	(w-1)(s-1)	$\sigma^2 + \sigma_{WP}^2 + k_2\sigma_{WD}^2 + k_3\sigma_{WS}^2$
W x D/S	(w-1)(d-s)	$\sigma^2 + \sigma_{WP}^2 + k_1\sigma_{WD}^2$
W x P/D/S	(w-1)(n-d)	$\sigma^2 + \sigma_{WP}^2$
Total	wn-1	

*Coefficients of variance components:

$$k_1 = \frac{1}{d-s}\left[n - \sum_i \frac{\sum_j n_{ij}^2}{n_{i.}}\right]$$

$$k_2 = \frac{1}{s-1}\left[\sum_i \frac{\sum_j n_{ij}^2}{n_{i.}} - \frac{1}{n}\sum_{ij} n_{ij}^2\right]$$

$$k_3 = \frac{1}{s-1}\left[n - \frac{1}{n}\sum_i n_{i.}^2\right]$$

$$k_4 = \frac{1}{n}\sum_{ij} n_{ij}^2$$

$$k_5 = \frac{1}{n}\sum_i n_{i.}^2$$

$$k_6 = \frac{w}{d-s}\left[n - \sum_i \frac{\sum_j n_{ij}^2}{n_{i.}}\right] = wk_1$$

$$k_7 = \frac{w}{s-1}\left[\sum_i \frac{\sum_j n_{ij}^2}{n_{i.}} - \frac{1}{n}\sum_{ij} n_{ij}^2\right] = wk_2$$

$$k_8 = \frac{w}{s-1}\left[n - \frac{1}{n}\sum_i n_{i.}^2\right] = wk_3$$

Tests of significance were performed by using the appropriate estimated mean squares, ignoring the unequal coefficients, and also by the procedure of synthesizing mean squares as presented by Tietjen and Moore (1968a) for the unequal number case. No discrepancy was found using the two methods.

The validity of the F-test proposed by Tietjen and Moore (1968a) is open to question (Tietjen and Moore, 1968b). The reason for this is that in the unbalanced case, the sums of squares, other than the error sum of squares, are not distributed as chi-square and they are not statistically independent (Sheffé, 1959, page 251).

A possible alternative procedure one should be aware of for making tests on variances is the so-called ''jackknife'' method (Arvesen, 1968). It is suggested as a procedure, not so much for estimation but used for testing or construction of confidence intervals. The t-test is used in the ''jackknife'' and is considered more robust against non-normality than is the F-test under the random effects model. The ''jackknife'' is also useful in certain unbalanced models and in testing linear combinations of variances as well as ratios and correlation coefficients. The application of this procedure in testing heritability and genetic correlation estimates appears to warrant further study.

Of particular interest in this analysis are the interactions of weeks by sires and weeks by dams within sires. A significant interaction component for weeks by sires would indicate that sire groups differ in their mean gain from week to week. An analogous interpretation could be put on a significant interaction component for weeks by dams within sires. These interaction components are, in part, a function of the genetic correlation between gains of an individual. Assuming equal variances of sire or dam groups across weeks, a genetic correlation of one would imply that the interaction component was zero (Robertson, 1959). Therefore, the average genetic correlation of gain in weight across weeks was investigated.

Genetic Correlation Among Gains in Body Weight

Using a modification of the method presented by Yamada (1962) for the mixed model, genetic correlations were calculated from the variance components of an analysis of variance of gains in weekly body weight. The average genetic correlation over weeks was estimated for each population using the following equation:

$$r_g = \frac{(\sigma_S^2 + \sigma_D^2) - \frac{1}{w}(\sigma_{WS}^2 + \sigma_{WD}^2)}{(\sigma_S^2 + \sigma_D^2) + \frac{w-1}{w}(\sigma_{WS}^2 + \sigma_{WD}^2) - V[\sigma_{G_i}]}$$

where: σ_S^2 = sire component of variance

σ_D^2 = dam component of variance

$\sigma_S^2 + \sigma_D^2$ = variance among full sib groups

σ_{WS}^2 = weeks by sire interaction component of variance

σ_{WD}^2 = weeks by dam interaction component of variance

w = number of weeks (45)

$V[\sigma_{G_i}]$ = variance of weekly between full sib group standard deviations, $i=0,\ldots, 44$.

The genetic interpretation of the components of variance in the mixed model are as follows:

$$\sigma^2_S = [t'r_g + \frac{1}{w} t'(1-r_g)] \ \sigma^2_T$$

$$\sigma^2_D = [tr_g + \frac{1}{w} t(1-r_g)] \ \sigma^2_T$$

$$\sigma^2_{WS} = t'(1-r_g) \ \sigma^2_T$$

$$\sigma^2_{WD} = t(1-r_g) \ \sigma^2_T$$

where: t' and t are the paternal and maternal half sib phenotypic correlations respectively, r_g is the genetic correlation between gains, and σ^2_T is the total phenotypic variance. The estimated genetic correlation is an average correlation among gains in all weeks.

Development of Theoretical Relations Among Body Weights and Gains

Change in Mean and Variance of Body Weight

As pointed out earlier, body weight is a trait in which the mean and variance are related. The weight, W_t of any individual at time t, can be expressed as the sum of the weight at an earlier age, W_{t-1}, and the gain in weight, G, between the two ages ($W_t = W_{t-1} + G$). The fact that the weight at time $t-1$ is part of the weight at t indicates that there is a part-whole relationship between weights taken on the same individual at different times. Since the gain in weight at different ages is different for individuals, this part-whole relationship implies that the variance of body weight will change over time. The theory of the change in the variance of body weight has been discussed by Monteiro and Falconer (1966).

The variance of weight at time $\underline{t}$ can be partitioned into its components:

$$V(W_t) = V(W_{t-1}) + V(G) + 2\ \mathrm{Cov}(W_{t-1},G).$$

The increase or decrease in the variance of weight between the two ages would be:

$$\begin{aligned}\Delta V(W) &= V(W_t) - V(W_{t-1}) \\ &= V(G) + 2\ \mathrm{Cov}(W_{t-1},G).\end{aligned}$$

Since the variance of the gain can never be negative, any decline in the variance of weight must come about because of a negative covariance between weight at time $\underline{t-1}$ and the subsequent gain. This result leads to a study of the biometrical relationships among weights and gains.

Biometrical Relations Among Weights and Gains

The biometrical relations among and within body weights and gains can be seen using the following relationships:

$$W_t = W_{t-1} + G_{t-1}$$

$$W_{t-1} = W_t - G_{t-1}$$

$$G_{t-1} = W_t - W_{t-1}$$

where: W_{t-1} = the weight at time <u>t-1</u>

W_t = the weight at time <u>t</u>

G_{t-1} = the gain in weight between times <u>t-1</u> and <u>t</u>.

Let:

σ_X denote the standard deviation of <u>X</u>

$V(X)$, σ_X^2 denote the variance of <u>X</u>

$Cov(XY)$ denote the covariance between <u>X</u> and <u>Y</u>.

<u>The Correlation Between Consecutive Weights</u>. The expected correlation between consecutive weights is:

$$r_{W_{t-1},W_t} = \frac{Cov(W_{t-1},W_t)}{\sigma_{W_{t-1}}\ \sigma_{W_t}} = \frac{Cov(W_{t-1},W_{t-1}+G_{t-1})}{\sigma_{W_{t-1}}\ \sigma_{W_t}}$$

$$= \frac{\sigma^2_{W_{t-1}} + r_{W_{t-1},G_{t-1}}\ \sigma_{W_{t-1}}\ \sigma_{G_{t-1}}}{\sigma_{W_{t-1}}\ \sigma_{W_t}}$$

$$r_{W_{t-1},W_t} = \frac{\sigma_{W_{t-1}} + r_{W_{t-1},G_{t-1}}\ \sigma_{G_{t-1}}}{\sigma_{W_t}} .$$

When the correlation between consecutive weights is one,

$$\sigma_{W_t} = \sigma_{W_{t-1}} + r_{W_{t-1},G_{t-1}}\ \sigma_{G_{t-1}} .$$

In addition, for the standard deviations of weights to be equal, i.e.

$\sigma_{W_t} = \sigma_{W_{t-1}}$

$$r_{W_{t-1}, G_{t-1}} \sigma_{G_{t-1}} = 0.$$

The Correlation Between Consecutive Gains. The expected correlation between consecutive gains is:

$$r_{G_{t-1},G_t} = \frac{\mathrm{Cov}(G_{t-1},G_t)}{\sigma_{G_{t-1}} \sigma_{G_t}} = \frac{\mathrm{Cov}(W_t-W_{t-1})(W_{t+1}-W_t)}{[V(W_t-W_{t-1})V(W_{t+1}-W_t)]^{1/2}}$$

$$= \frac{\mathrm{Cov}(W_t,W_{t+1})+\mathrm{Cov}(W_{t-1},W_t)-\mathrm{Cov}(W_{t-1},W_{t+1})-V(W_t)}{[\{\sigma^2_{W_{t-1}} + \sigma^2_{W_t} -2\mathrm{Cov}(W_{t-1},W_t)\}\{\sigma^2_{W_{t+1}} + \sigma^2_{W_t} -2\mathrm{Cov}(W_t,W_{t+1})\}]^{1/2}}$$

$$r_{G_{t-1},G_t} = \frac{r_{W_t,W_{t+1}} \sigma_{W_t} \sigma_{W_{t+1}} + r_{W_{t-1},W_t} \sigma_{W_{t-1}} \sigma_{W_t} - r_{W_{t-1},W_{t+1}} \sigma_{W_{t-1}} \sigma_{W_{t+1}} - \sigma^2_{W_t}}{[\{\sigma^2_{W_{t-1}} + \sigma^2_{W_t} -2r_{W_{t-1},W_t} \sigma_{W_{t-1}} \sigma_{W_t}\}\{\sigma^2_{W_{t+1}} + \sigma^2_{W_t} -2r_{W_t,W_{t+1}} \sigma_{W_t} \sigma_{w_{t+1}}\}]^{1/}}$$

Thus, r_{G_{t-1},G_t} is negative when:

$$\sigma_{W_t}\{r_{W_t,W_{t+1}} \sigma_{W_{t+1}} + r_{W_{t-1},W_t} \sigma_{W_{t-1}}\} < \{r_{W_{t-1},W_{t+1}} \sigma_{W_{t-1}} \sigma_{W_{t+1}} + \sigma^2_{W_t}\}.$$

If consecutive weights are uncorrelated, $r_{W_{t-1},W_t} = r_{W_t,W_{t+1}} = 0$, then

$$r_{G_{t-1},G_t} = \frac{-r_{W_{t-1},W_{t+1}} \sigma_{W_{t-1}} \sigma_{W_{t+1}} - \sigma^2_{W_t}}{[\{\sigma^2_{W_{t-1}} + \sigma^2_{W_t}\}\{\sigma^2_{W_{t+1}} + \sigma^2_{W_t}\}]^{1/2}}.$$

If $r_{W_{t-1},W_{t+1}}$ also equals zero, then

$$r_{G_{t-1},G_t} = \frac{-\sigma^2_{W_t}}{[\{\sigma^2_{W_{t-1}} + \sigma^2_{W_t}\}\{\sigma^2_{W_{t+1}} + \sigma^2_{W_t}\}]^{1/2}},$$

which is always negative. If consecutive weights are perfectly correlated, $r_{W_{t-1},W_t} = r_{W_t,W_{t+1}} = 1$, then

$$r_{G_{t-1},G_t} = \frac{\sigma_{W_t}\sigma_{W_{t+1}} + \sigma_{W_{t-1}}\sigma_{W_t} - r_{W_{t-1},W_{t+1}}\sigma_{W_{t-1}}\sigma_{W_{t+1}} - \sigma^2_{W_t}}{[\{\sigma^2_{W_{t-1}} + \sigma^2_{W_t} - 2\sigma_{W_{t-1}}\sigma_{W_t}\}\{\sigma^2_{W_{t+1}} + \sigma^2_{W_t} - 2\sigma_{W_t}\sigma_{W_{t+1}}\}]^{1/2}}$$

which is negative when $\sigma_{W_t}\{\sigma_{W_{t+1}} + \sigma_{W_{t-1}}\} < \{r_{W_{t-1},W_{t+1}}\sigma_{W_{t-1}}\sigma_{W_{t+1}} - \sigma^2_{W_t}\}$.

If $r_{W_{t-1},W_{t+1}}$ also equals one, then

$$r_{G_{t-1},G_t} = \frac{\sigma_{W_t}\sigma_{W_{t+1}} + \sigma_{W_{t-1}}\sigma_{W_t} - \sigma_{W_{t-1}}\sigma_{W_{t+1}} - \sigma^2_{W_t}}{[\{\sigma^2_{W_{t-1}} + \sigma^2_{W_t} - 2\sigma_{W_{t-1}}\sigma_{W_t}\}\{\sigma^2_{W_{t+1}} + \sigma^2_{W_t} - 2\sigma_{W_t}\sigma_{W_{t+1}}\}]^{1/2}}$$

which is negative when $\sigma_{W_t}\{\sigma_{W_{t+1}} + \sigma_{W_{t-1}}\} < \{\sigma_{W_{t-1}}\sigma_{W_{t+1}} - \sigma^2_{W_t}\}$. Note that when the correlations among the weights are zero, and the variance of the weights are equal, then $r_{G_{t-1},G_t} = -0.50$.

<u>The Correlation Between Gain and Subsequent Weight</u>. The expected correlation between gain and the subsequent weight is:

$$r_{G_{t-1},W_t} = \frac{\mathrm{Cov}(G_{t-1},W_t)}{\sigma_{G_{t-1}}\sigma_{W_t}} = \frac{\mathrm{Cov}(W_t-W_{t-1},W_t)}{[V(W_t-W_{t-1})V(W_t)]^{1/2}}$$

$$= \frac{\sigma_{W_t}-r_{W_{t-1},W_t}\sigma_{W_{t-1}}}{[\sigma^2_{W_t}+\sigma^2_{W_{t-1}}-2r_{W_{t-1},W_t}\sigma_{W_{t-1}}\sigma_{W_t}]^{1/2}} .$$

The correlation between gain and the next weight is negative when:

$$\sigma_{W_t} < r_{W_{t-1},W_t}\,\sigma_{W_{t-1}} .$$

If the correlation is zero between successive weights, $r_{W_{t-1},W_t} = 0$, then

$$r_{G_{t-1},W_t} = \frac{\sigma_{W_t}}{[\sigma^2_{W_t}+\sigma^2_{W_{t-1}}]^{1/2}} ,$$

which is always positive. If the correlation is one between successive weights, $r_{W_{t-1},W_t} = 1$, then

$$r_{G_{t-1},W_t} = \frac{\sigma_{W_t}-\sigma_{W_{t-1}}}{[\sigma^2_{W_t}+\sigma^2_{W_{t-1}}-2\sigma_{W_t}\sigma_{W_{t-1}}]^{1/2}} ,$$

which is negative when $\sigma_{W_t} < \sigma_{W_{t-1}}$.

The Correlation Between Weight and Subsequent Gain. The expected correlation between weight and subsequent gain is:

$$r_{W_{t-1},G_{t-1}} = \frac{\mathrm{Cov}(W_{t-1},G_{t-1})}{\sigma_{W_{t-1}}\,\sigma_{G_{t-1}}} = \frac{\mathrm{Cov}(W_{t-1},W_t-W_{t-1})}{[V(W_{t-1})V(W_t-W_{t-1})]^{1/2}}$$

$$= \frac{r_{W_{t-1},W_t}\sigma_{W_t} - \sigma_{W_{t-1}}}{[\sigma^2_{W_t} + \sigma^2_{W_{t-1}} - 2r_{W_{t-1},W_t}\sigma_{W_{t-1}}\sigma_{W_t}]^{1/2}} .$$

The correlation between weight and the next gain is negative when:

$$r_{W_{t-1},W_t}\,\sigma_{W_t} < \sigma_{W_{t-1}} .$$

If the correlation is zero between successive weights, $r_{W_{t-1},W_t} = 0$, then

$$r_{W_{t-1},G_{t-1}} = \frac{-\sigma_{W_{t-1}}}{[\sigma^2_{W_t} + \sigma^2_{W_{t-1}}]^{1/2}} ,$$

which is always negative. If $r_{W_{t-1},W_t} = 1$,

$$r_{W_{t-1},G_{t-1}} = \frac{\sigma_{W_t} - \sigma_{W_{t-1}}}{[\sigma^2_{W_t} + \sigma^2_{W_{t-1}} - 2\sigma_{W_t}\,\sigma_{W_{t-1}}]^{1/2}}$$

which is negative when $\sigma_{W_t} < \sigma_{W_{t-1}}$.

It is interesting to note that because of the part-whole relationship between weights, the correlations developed above are not independent since they involve the correlation between successive weights. Thus, one can not attribute a cause and effect relationship between the correlations for a change in one of them. The development includes the case when successive weights are uncorrelated. This is an unrealistic situation as the results will show, nevertheless it is of theoretical interest.

RESULTS AND DISCUSSION

Relationships Among Body Weights

Means, Standard Deviations and Coefficients of Variation

The means, phenotypic standard deviations and phenotypic coefficients of variation were calculated from individually observed weekly body weights. They are presented in Tables A6-A9 and plotted in Figures B1-B4 (Appendix B) for each population.

Means of Weekly Body Weights. The means of the observed weekly body weights for the four populations are plotted in Figure 1.1. There is a discontinuity in the mean weight curve between 10 and 11 weeks of age. This could be explained by the fact that during this interval all birds were debeaked making feeding difficult. At hatching, there were essentially no sex differences for body weight. At 45 weeks the males were heavier than the females in both lines. Both sexes of the RIR line were heavier than both sexes of the WL line. The maximum mean weight achieved during the experiment was 3192.0 gm and 2320.0 gm for RIR males and females, respectively. For the WL line the maximum mean weights were 2129.2 gm and 1740.4 gm for the males and females, respectively. For all populations except the RIR females, the maximum weight was reached before the end of the experiment. The decline in mean body weight during the latter part of the experiment might be attributed to environmental influences, since it is expected that body weight should follow an increasing curve.

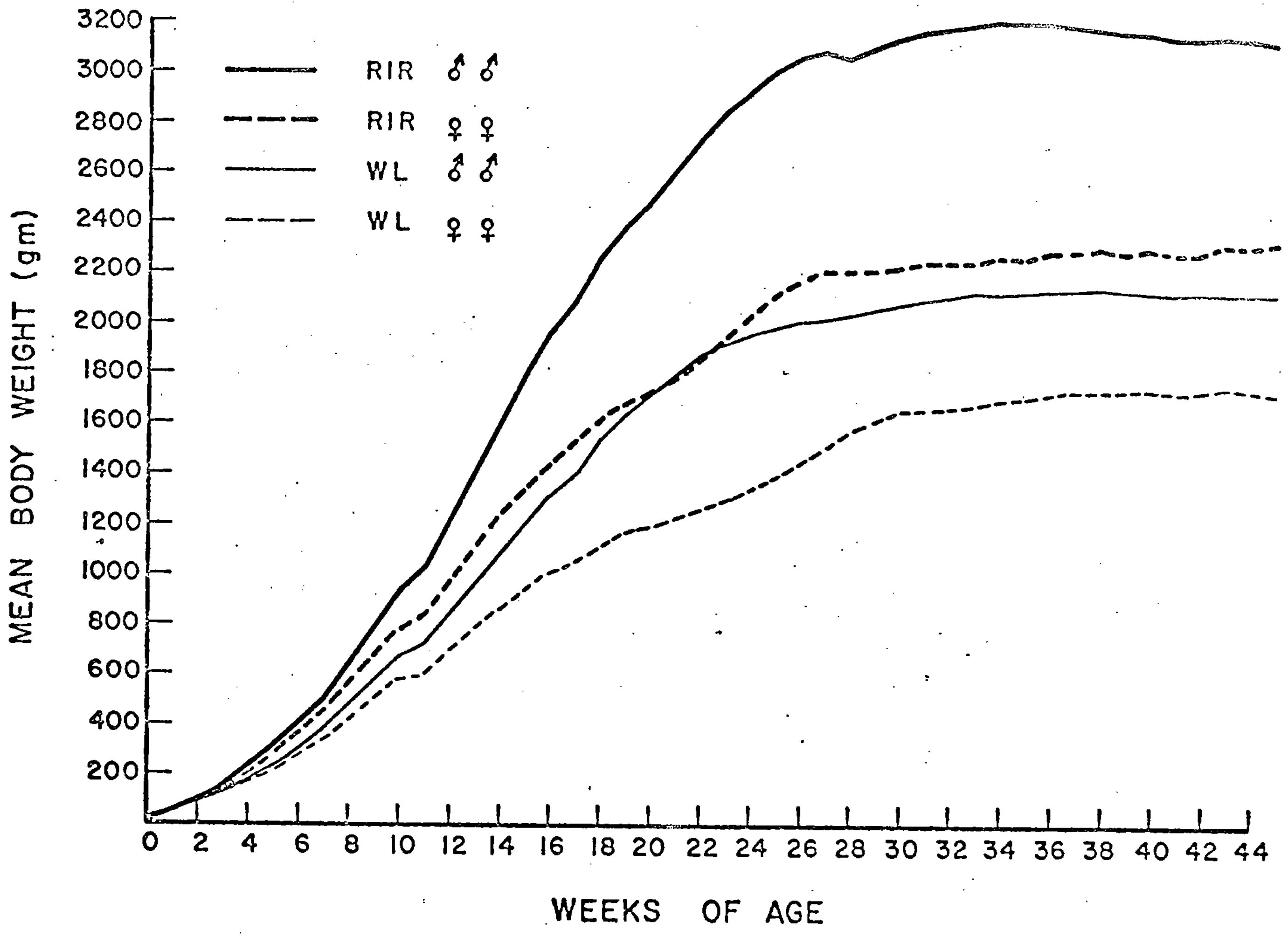


Figure 1.1. Means of Weekly Body Weights for Rhode Island Red and White Leghorn Males and Females

Standard Deviations of Weekly Body Weights. The standard deviations of weekly body weights are presented, by populations, in Figure 1.2. The standard deviations of hatching weights were essentially the same in all populations; the value being about 4.00 gm. That the mean and standard deviation (or variance) are related in a characteristic such as body weight, was borne out by these graphs. The trend of the variance generally increased over time, as did the mean body weight.

Several times, however, the variance declined from the preceeding week. In the WL females, for example, the variance at 11 weeks of age was less than at 10 weeks. The decrease in variance of weights in the WL female population is indicative of compensatory growth (Monteiro and Falconer, 1966). This will be discussed further in a later section.

At the conclusion of the experiment, both sexes of the RIR line had more variable body weights than either sex of the WL line. The four populations were ranked in body weight the same as they were ranked in regard to variability. Because of the relationship between the mean and variance, the coefficients of variation were examined.

Phenotypic and Genetic Coefficients of Variation. The phenotypic coefficients of variation for weekly body weights (Figure 1.3) showed an increase to a maximum at about three to six weeks of age. Thereafter, there was a decrease until the values leveled off from about 15 weeks of age at 12 to 13 percent. The curves increased again at 20 to 22 weeks indicating an increase in the variation of weight relative to the mean probably due to the differences among individuals in the onset of puberty.

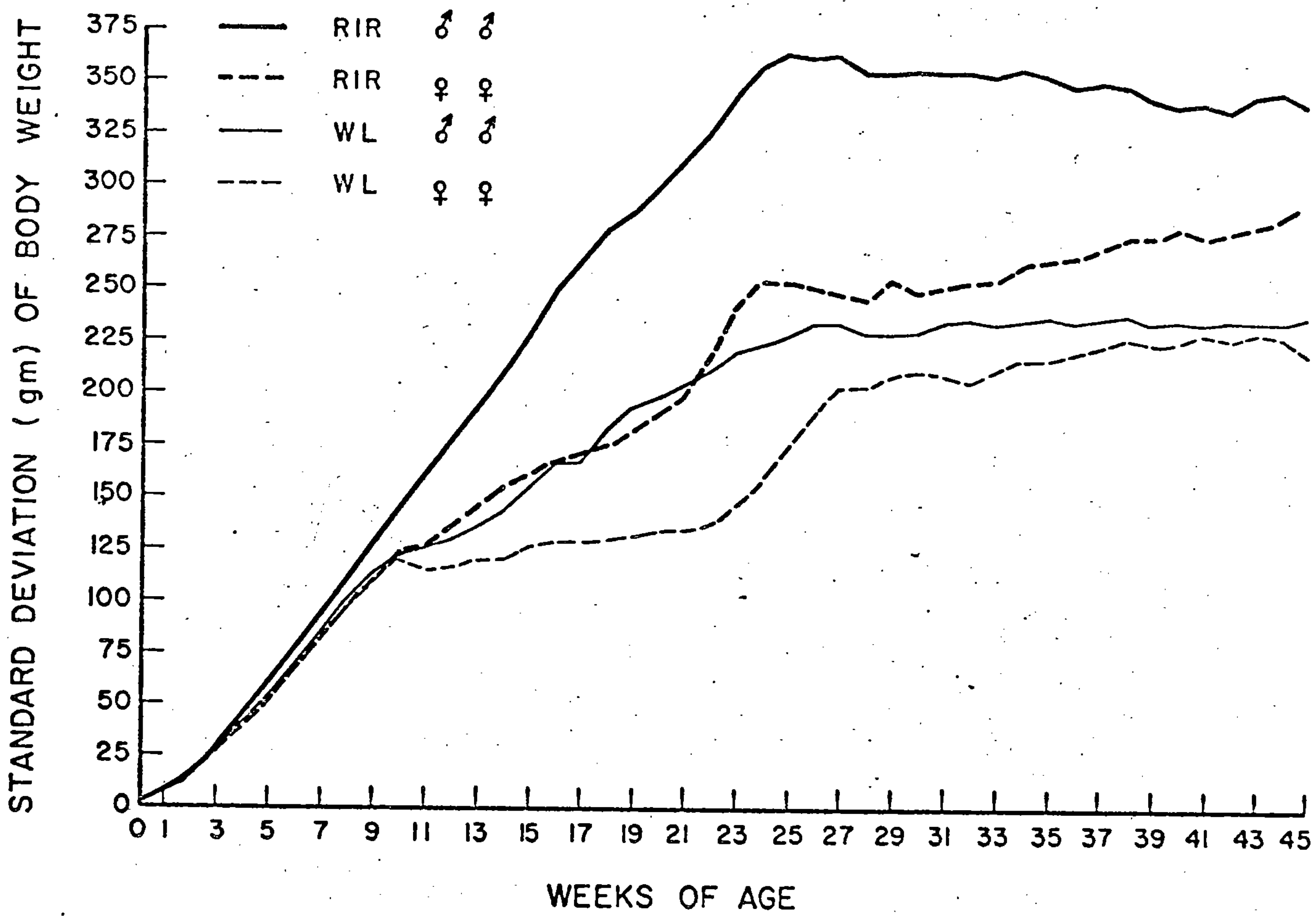


Figure 1.2. Standard Deviations of Weekly Body Weights for Rhode Island Red and White Leghorn Males and Females

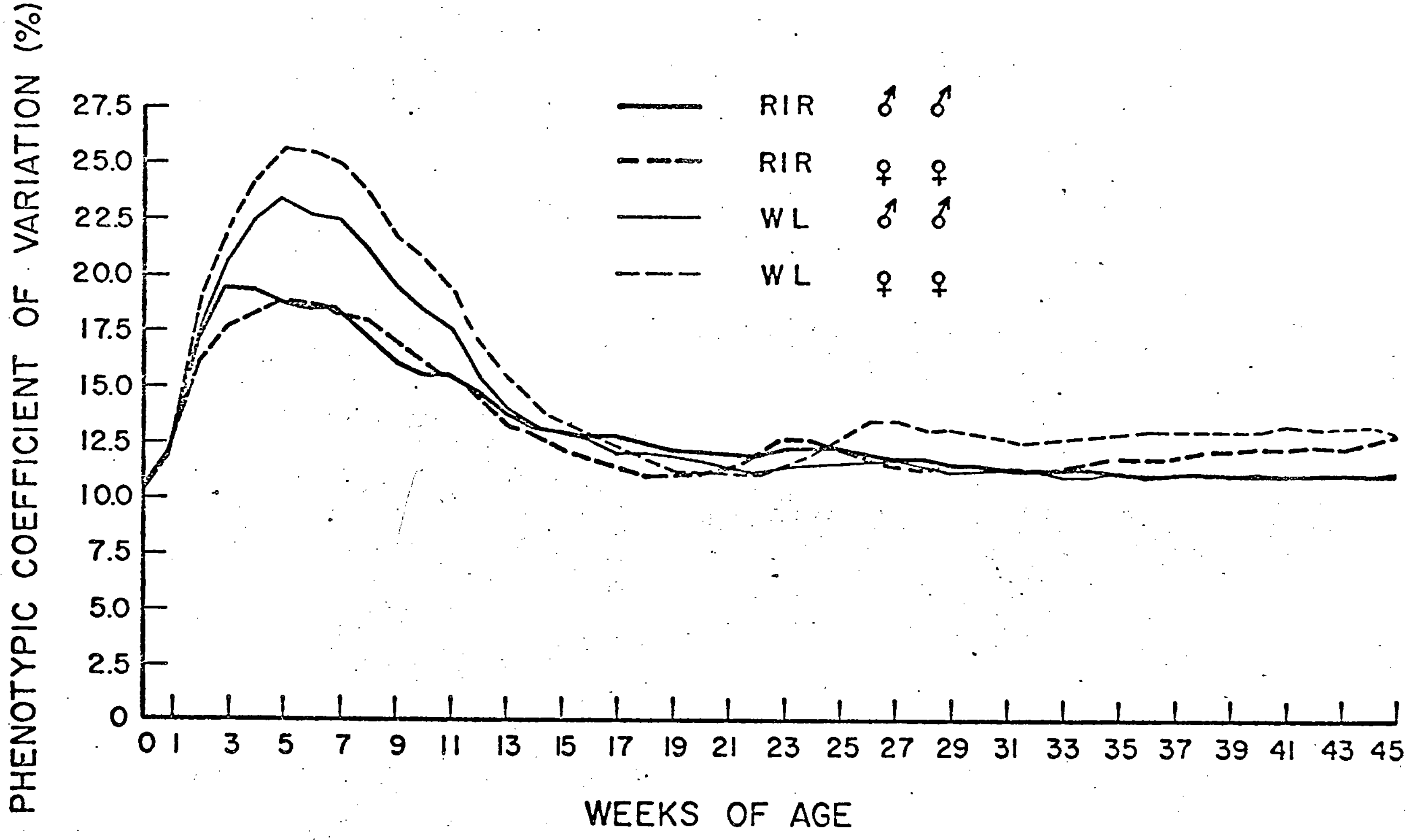


Figure 1.3. Phenotypic Coefficients of Variation of Weekly Body Weights for Rhode Island Red and White Leghorn Males and Females

The theory that was developed for the change in variance holds true not only for phenotypic variance but genetic variance as well (see Table A10). Estimates of the genetic coefficients of variation (based on sire plus dam components of variance) by weeks are presented in Tables A11-A14 and plotted in Figure 1.4 for all populations. The genetic coefficient of variation, unlike its phenotypic counterpart, started with a decline in all populations except the RIR males. This is probably an indication of the non-genetic influences, particularly the maternal effects, important in early life. After two weeks of age, the genetic coefficient of variation increased to a maximum at between four to six weeks of age. Then, after a decline, it leveled off at a value between 9 and 11 percent. As in the case of the phenotypic coefficient of variation, the genetic coefficient of variation began to increase at about 19 to 22 weeks of age. This was especially noticeable in the females. The secondary increase of the genetic coefficient of variation at about 26 weeks of age is indicative of the effect of the heritability of age at sexual maturity.

Kinney et al. (1968) have shown that in the North Central Regional (NCR) WL female population, from which the birds used here are a sample, the mean age at sexual maturity, as measured by weeks to first egg, was 25.0 in 1964-65. The heritability estimate (pooled over years) was about 0.32. During the same period for the RIR female population, the mean age at sexual maturity was 24.2 with a pooled heritability estimate of 0.33 (Kinney and Lowe, 1968). Thus, a possible explanation for the increase in the genetic coefficient of variation is that families that come into sexual maturity together will, at that time, tend to have

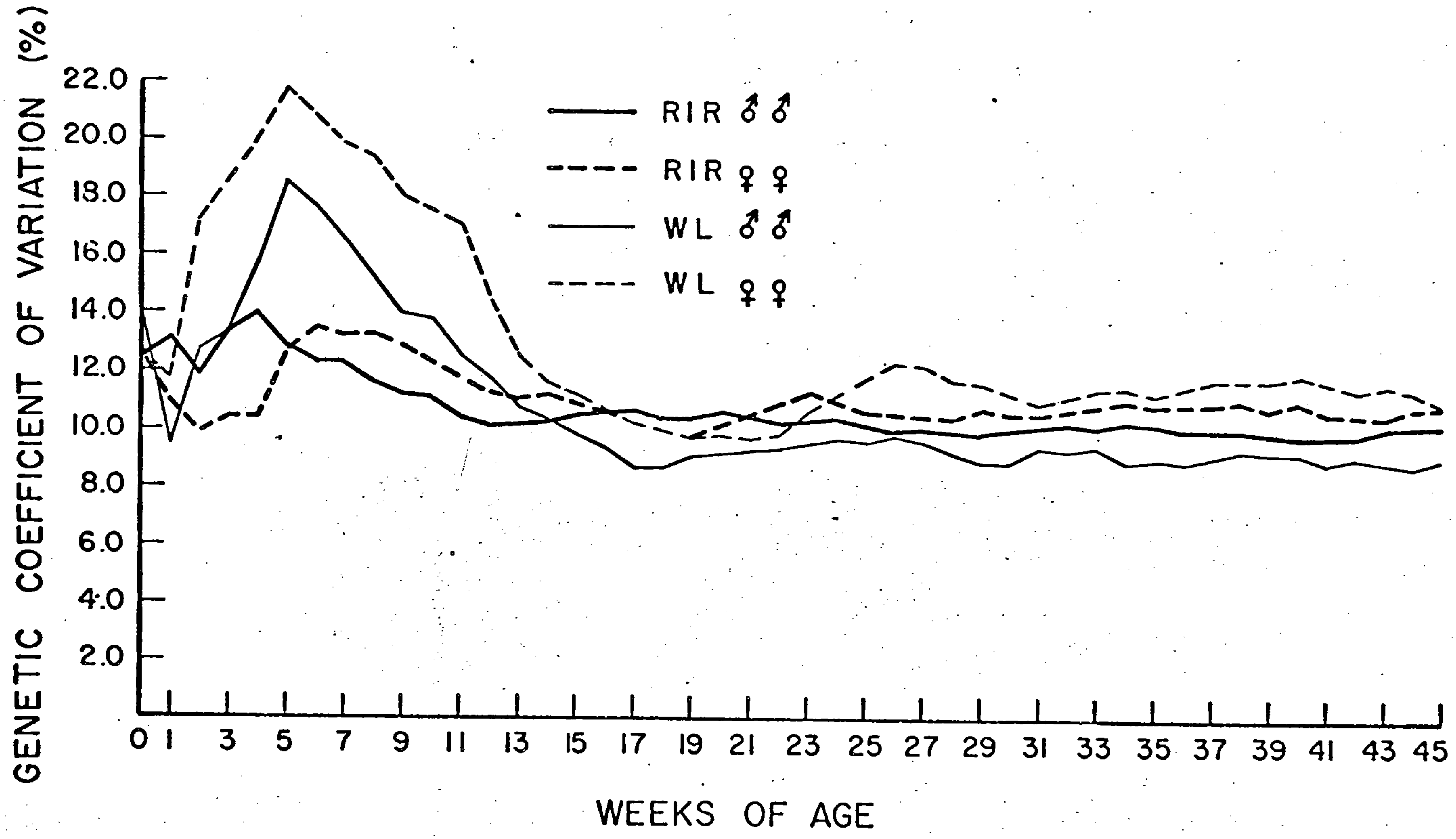


Figure 1.4. Genetic Coefficients of Variation of Weekly Body Weights for Rhode Island Red and White Leghorn Males and Females

a higher body weight simply because of the increase in the size of the ovary.

It is often heard that in order to make maximum genetic gain, selection should be made when genetic variance is at a maximum. From the point of view of the poultry farmer, interest is usually centered on selection for increased body weight only at a specific time, for example at eight weeks of age. If, however, interest is on utilizing the genetic variance for a theoretical study of say selection limits, then we would want to select for body weight at an age when maximum genetic gain is possible. With all other parameters being equal, the theory dictates that selection for body weight with maximum gain should be at an age when heritability is a maximum. Therefore, what is important in selection and predicting gains due to selection is the estimate of the ratio of the additive genetic variance to the total phenotypic variance; the heritability. The results of a study of this parameter will be presented in the next section.

Heritability Estimates of Weekly Body Weights

The estimates of heritability for body weights based on sire (Table A15), dam (Table A16) and sire plus dam (Table A17) components as well as their standard errors were calculated by weeks for all populations. The weekly estimates are plotted in Figures 1.5-1.8.

To briefly describe the general results, attention will be focused on those heritability estimates based on the sum of the sire and dam components of variance, h^2_{S+D}. Since there is a negative covariance between the estimates of the sire and dam variance components (Osborne and Paterson, 1952), an overestimate of the dam component would result

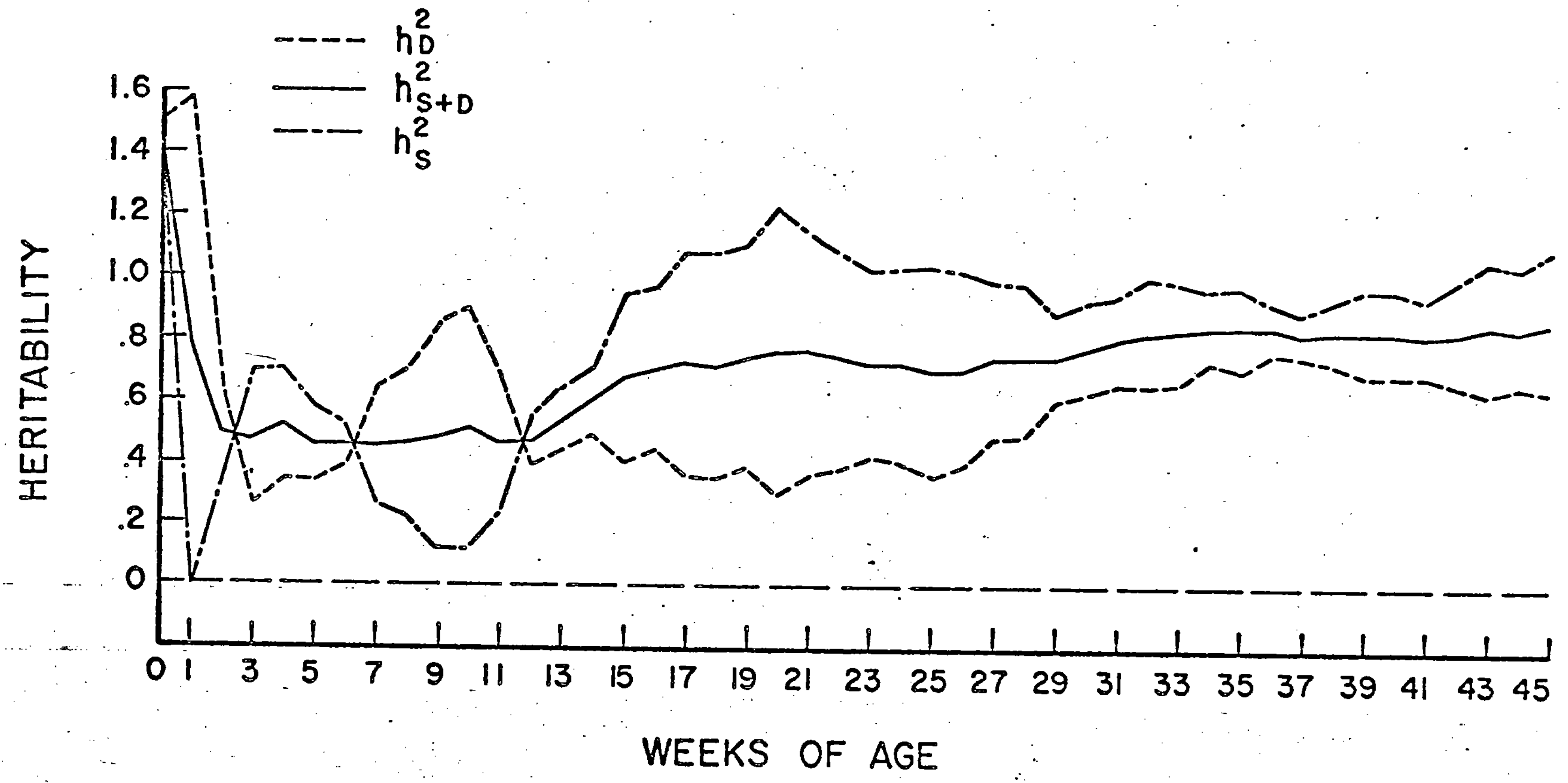


Figure 1.5. Heritability Estimates of Weekly Body Weights for Rhode Island Red Males

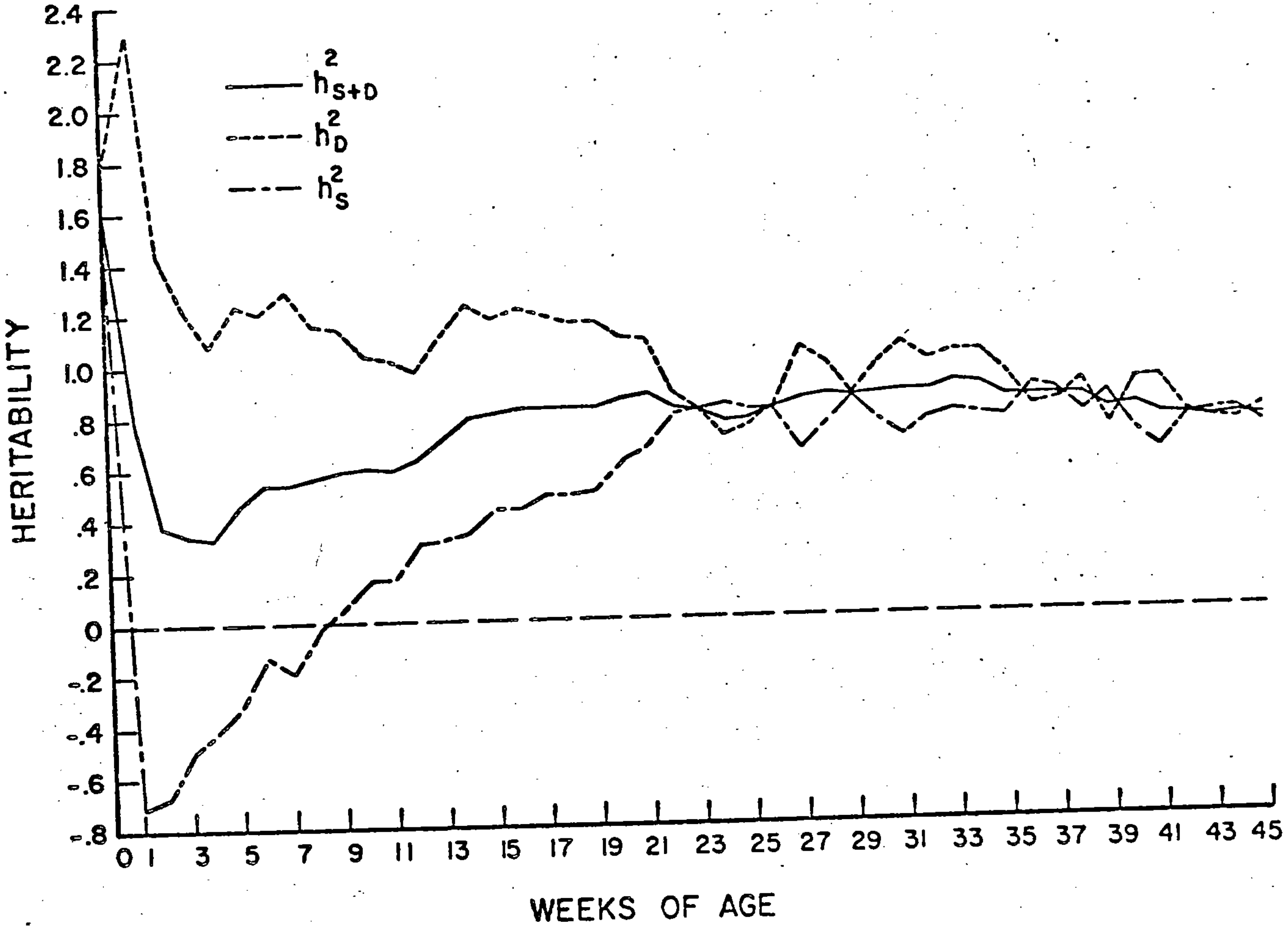


Figure 1.6. Heritability Estimates of Weekly Body Weights for Rhode Island Red Females

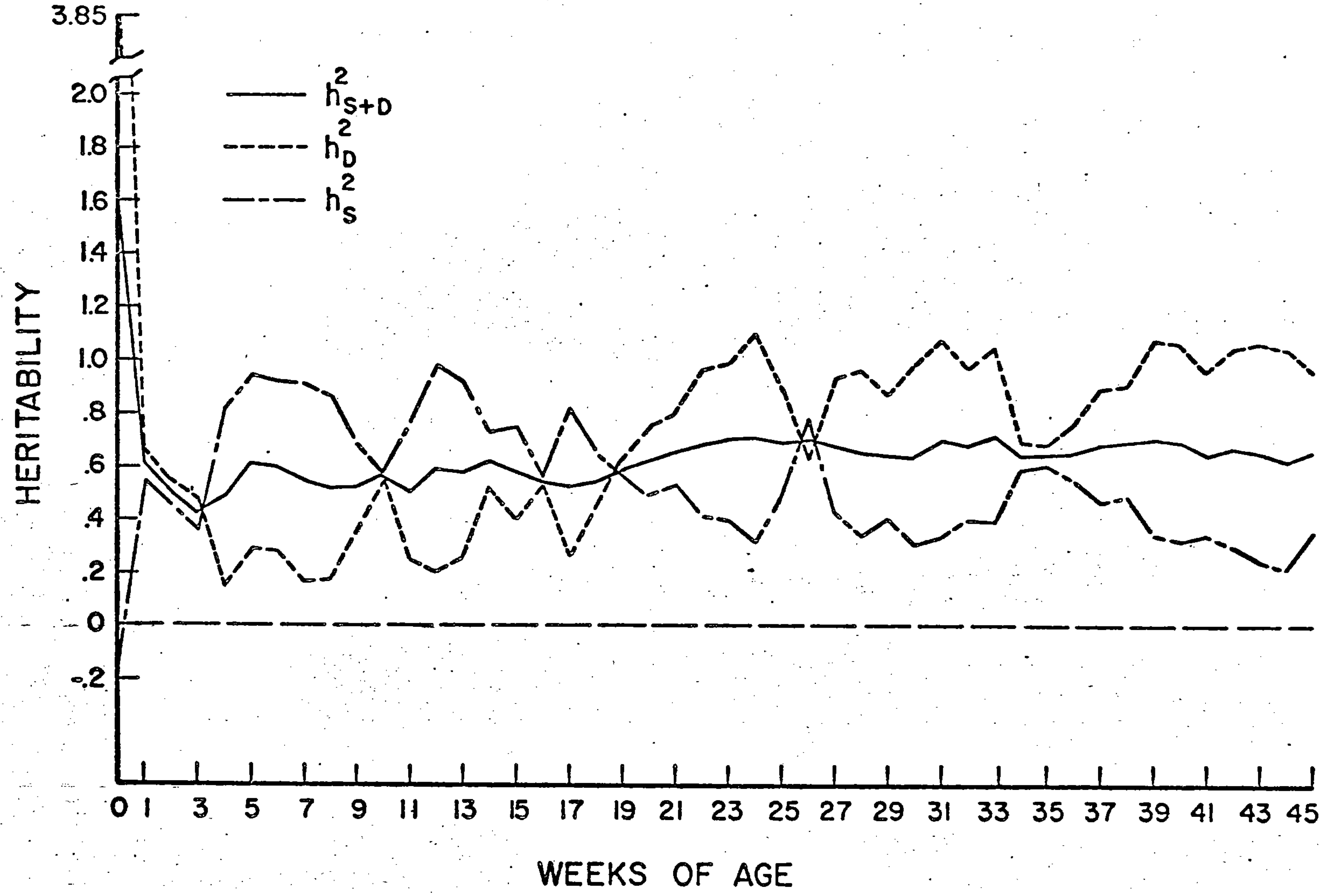


Figure 1.7. Heritability Estimates of Weekly Body Weights for White Leghorn Males

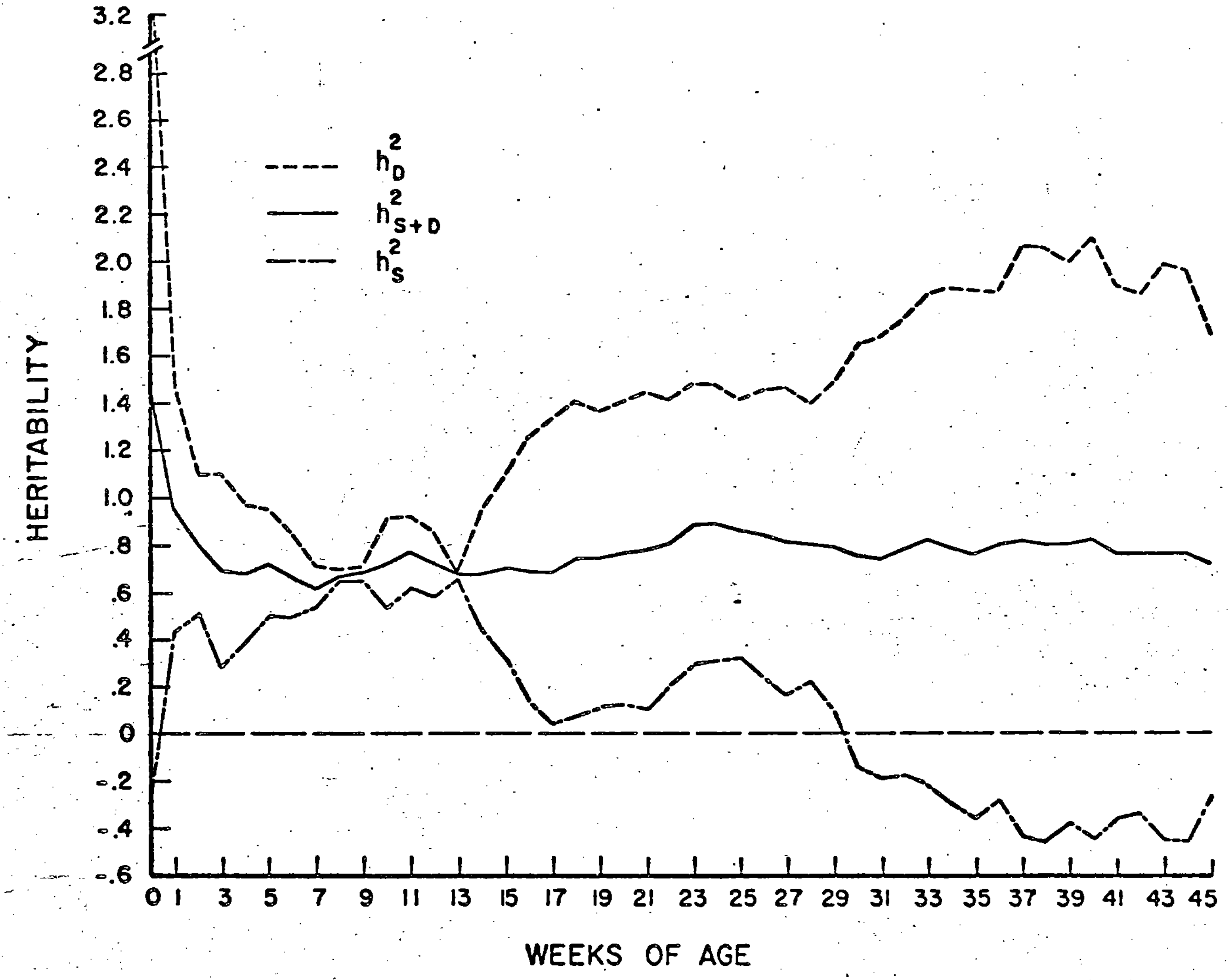


Figure 1.8. Heritability Estimates of Weekly Body Weights for White Leghorn Females

in an underestimate of the sire component and vice versa. Notice the almost mirror image the sire component heritability (h^2_S) makes with the dam component heritability (h^2_D) (see Figures 1.5-1.8). For this reason, it was thought that, for the overall picture, the estimate of heritability (h^2_{S+D}) based on the correlation between full sibs (an average of the two heritabilities) should be used from a purely statistical viewpoint. However, from a genetic viewpoint, in a characteristic such as body weight there are usually maternal effects and possibly also dominance and epistatic variances that would bias the estimate of additive genetic variance and, therefore, heritability upward when the estimate includes the dam component of variance.

The initial heritability estimate (h^2_{S+D}) was greater than one in all populations. After a decline to a value of about 0.4 to 0.7, the heritabilities started to increase. At the end of the experiment the heritabilities were 0.86 and 0.66 for the males of the RIR and WL lines, respectively. For the females of the RIR and WL lines, the values were 0.74 and 0.72. Because of the magnitude of the standard errors of the estimates of heritability further study of this parameter would be appropriate with larger numbers in the populations.

Gill and Jensen (1968) have shown that for a given heritability and with equal numbers of total observations, the probability of obtaining a negative estimate of heritability from the dam component with two full sibs per mating is greater than when estimating heritability from the sire component. This is not surprising since there are more progeny per sire than per dam thereby reducing the sampling error variance. They also found some indication of an increase in the number of negative estimates when there are disproportionate subclass numbers. Thus, when using the sire component of variance to estimate heritability it would be somewhat surprising to find a larger number of negative estimates than would be expected from sampling. This was exactly what happened, however, in the early ages of the RIR females and the later ages of the WL females. A reason for this will be proposed in the following section where the weekly estimates of sire and dam components in each population will be examined.

Sire and Dam Components of Variance. Tables A18 and A19 and Figures 1.9-1.12 present the estimates of the sire and dam components of variance from analyses of weekly body weights for the RIR and WL males and females. Of particular interest are the sire components in the RIR female and the WL female populations.

With reference first to the RIR female population, the questions to be answered were: 1) Why are there consistent negative estimates of sire components from one to eight weeks of age, and 2) Why do they become positive at 9 weeks of age? The answer to the first question was outlined in the section on Materials and Methods. Briefly, the argument stated that possibly a temporary maternal influence caused competition for food among half sibs and resulted in a negative estimate for the phenotypic correlation among half sibs.

A possible answer to the second question is that the females were establishing their peck order at this time. Guhl (1953) found that, in his flocks, aggressiveness in chicks appeared gradually and that the peck order did not develop until the chicks were eight to ten weeks of age. He also found that, all other things being equal, body weight or

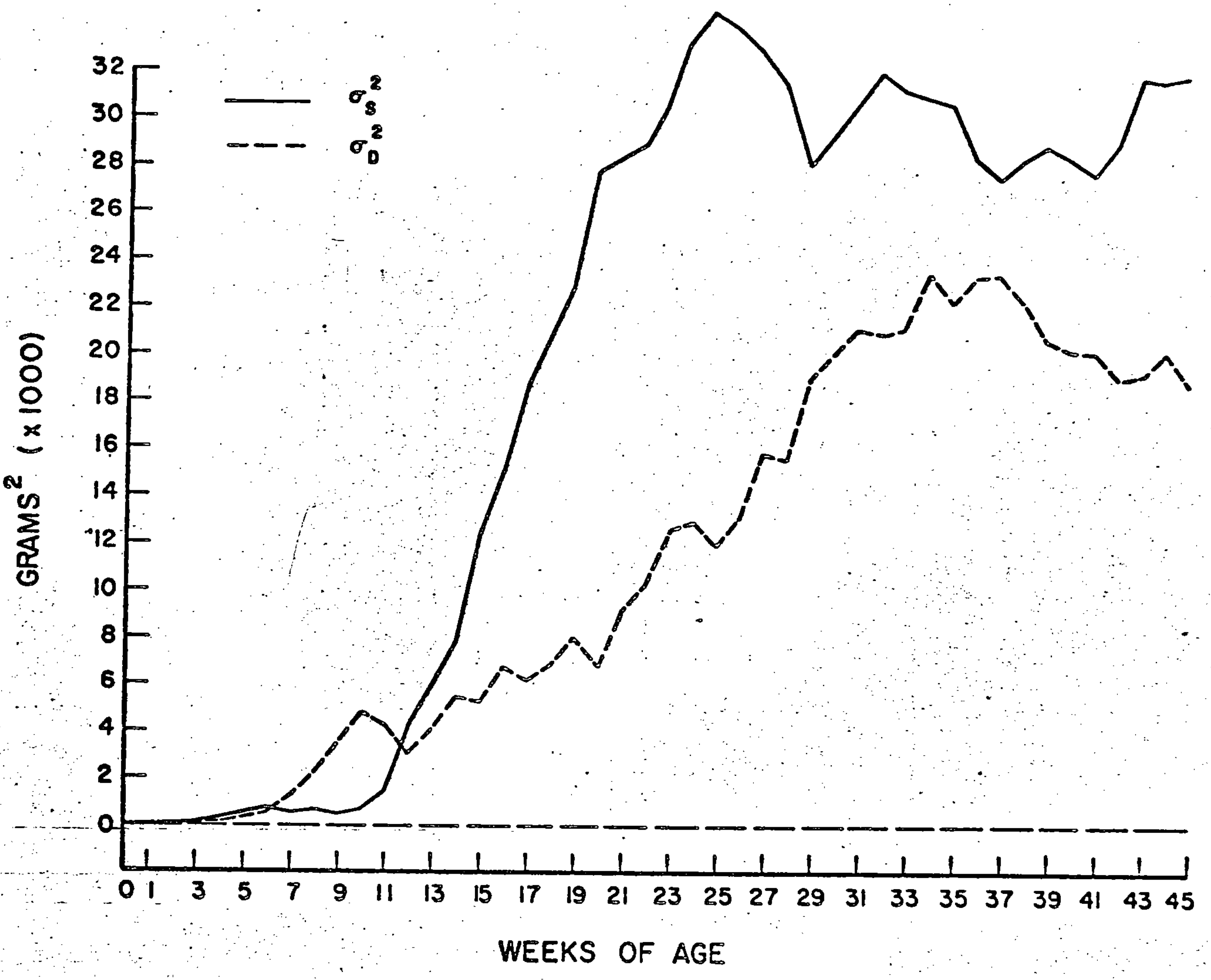


Figure 1.9. Sire and Dam Components of Variance Estimates of Weekly Body Weights for Rhode Island Red Males

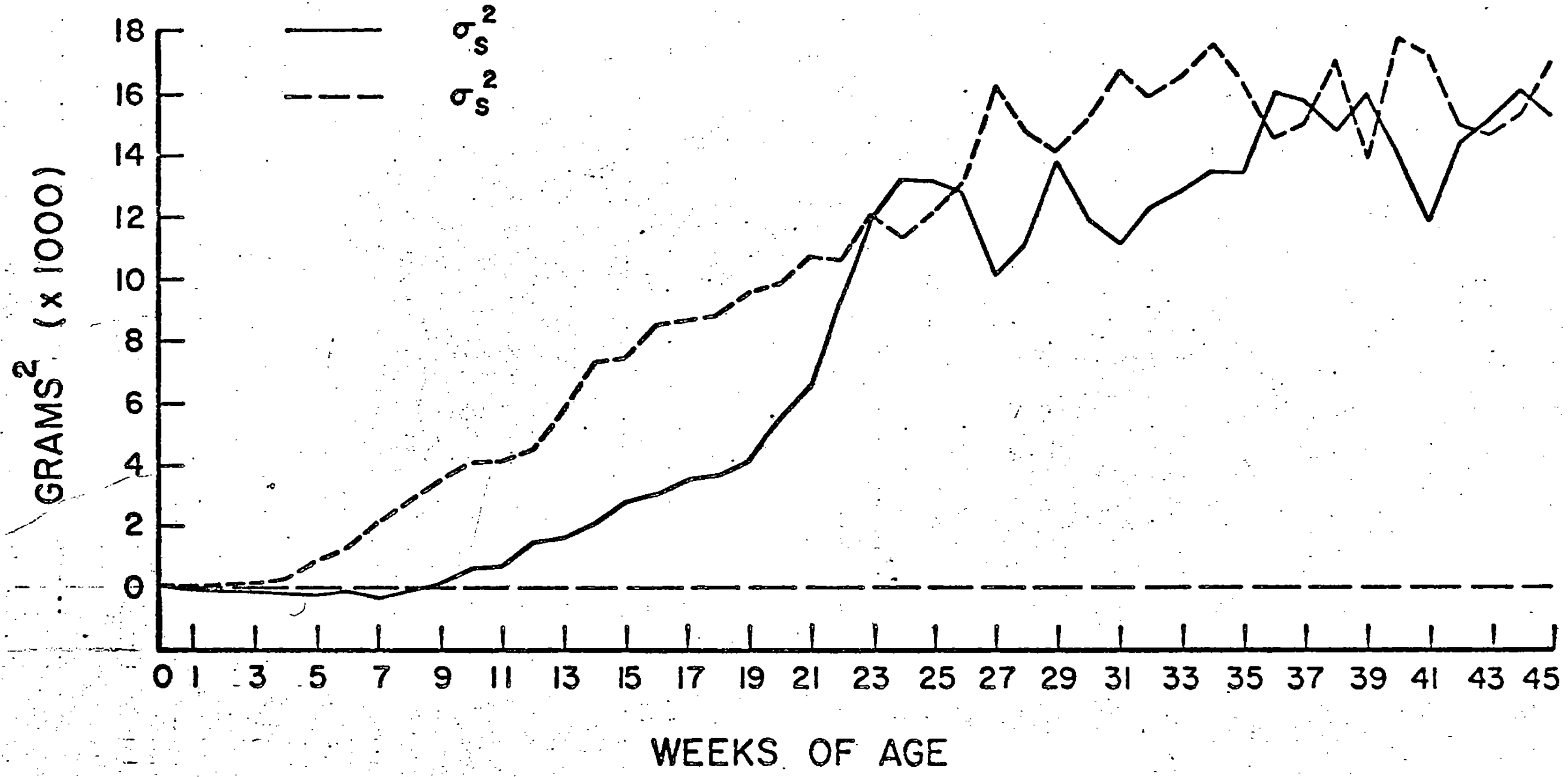


Figure 1.10. Sire and Dam Components of Variance Estimates of Weekly Body Weights for Rhode Island Red Females

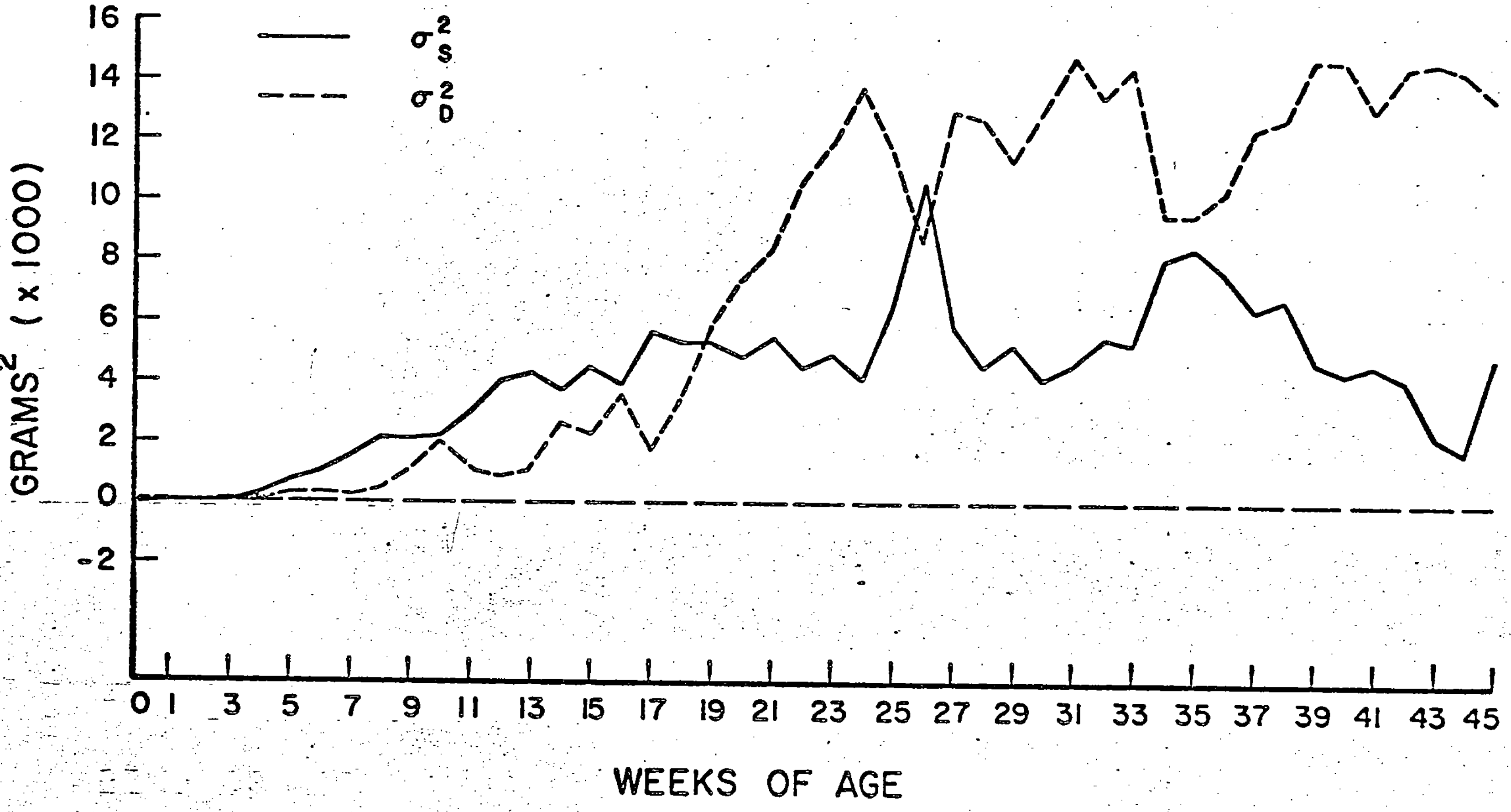


Figure 1.11. Sire and Dam Components of Variance Estimates of Weekly Body Weights for White Leghorn Males

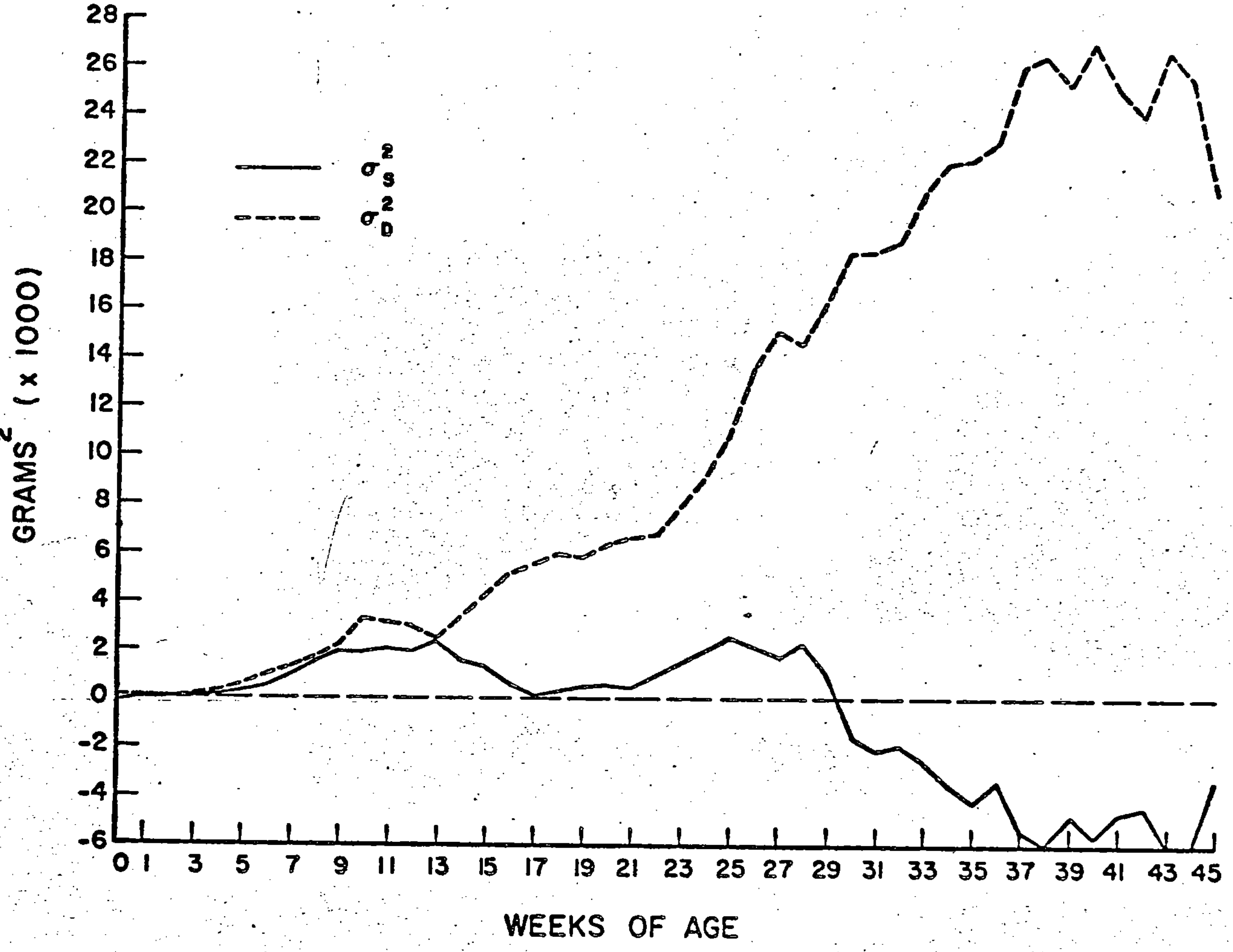


Figure 1.12. Sire and Dam Components of Variance Estimates of Weekly Body Weights for White Leghorn Females

strength is a determining factor influencing the attainment of social status. Recently, Craig (1968) found, in RIR lines (sampled from the NCR population) selected for high and low social dominance, that high social dominance was genetically associated with low weight at five months. However, the low selected line did not show an association with heavy weight.

Thus, the heavier siblings, when establishing their peck order, became more aggressive and assumed a dominant social position. Consequently, the more socially dominant siblings did not gain as much weight, and became closer in weight to their subordinate sibs. Further investigation along this line would be of interest since selection for body weight on a dam family basis may be influenced by inter-dam family social competition within sires.

The results of the WL females, i.e. consistent negative sire components from 30 weeks of age, will be explained briefly. Since there are no negative estimates for sire components after hatching time, it appears that the maternal influence in WL females is not as important as in the RIR females during the early life of the chicken. Thus, there would be less competition among half sibs until the peck order is established. Craig (1968) has found that selection for high social dominance is associated with heavy weight at five months of age in WL females. Thus, social dominance would lead to competition among half sibs for food with a consequent negative estimate for the phenotypic correlation between them. This then might be a cause for the negative sire component estimates after 30 weeks of age.

In comparing the two lines, the RIR line had smaller sire components of variance in the early ages of life, while the WL line had smaller sire components of variance in the later ages. This appears to be evidence for a larger maternal influence in the RIR line than in the WL line and gives support to the results presented by Craig.

Correlations Between Body Weights

Correlations Between Consecutive Body Weights. The correlations between consecutive weekly body weights for all populations are presented in Table A20 and plotted in Figure 1.13. As pointed out earlier, this type of correlation is representative of a relationship known as part-whole, since weight at some previous time is part of the whole weight at a later time. The correlations between the first and second, and second and third body weights were lower in all populations relative to the correlations between the following consecutive weights. This is probably due to the maternal influence of the hen on the chick. The maternal effect appears to have decreased by the third week with regard to an individual's own body weight so that the heavier individuals remained heavy. The correlations, in general, rose until about six or seven weeks and leveled off at almost one thereafter. In the females of both lines, there was a decline and rise in the correlations at about the time of sexual maturity. The decline probably is due to the sudden increase in the size of the ovary affecting the body weight.

Correlations Between Initial and Successive Body Weights. The correlations between weight at hatching and weekly weights at later ages are presented for each population in Table A21 and plotted in Figure 1.14. The correlations initially declined until about two or three weeks of age and then remained steady at about 0.30 for the WL line and about 0.15 for the RIR line. The decrease in the correlations is probably

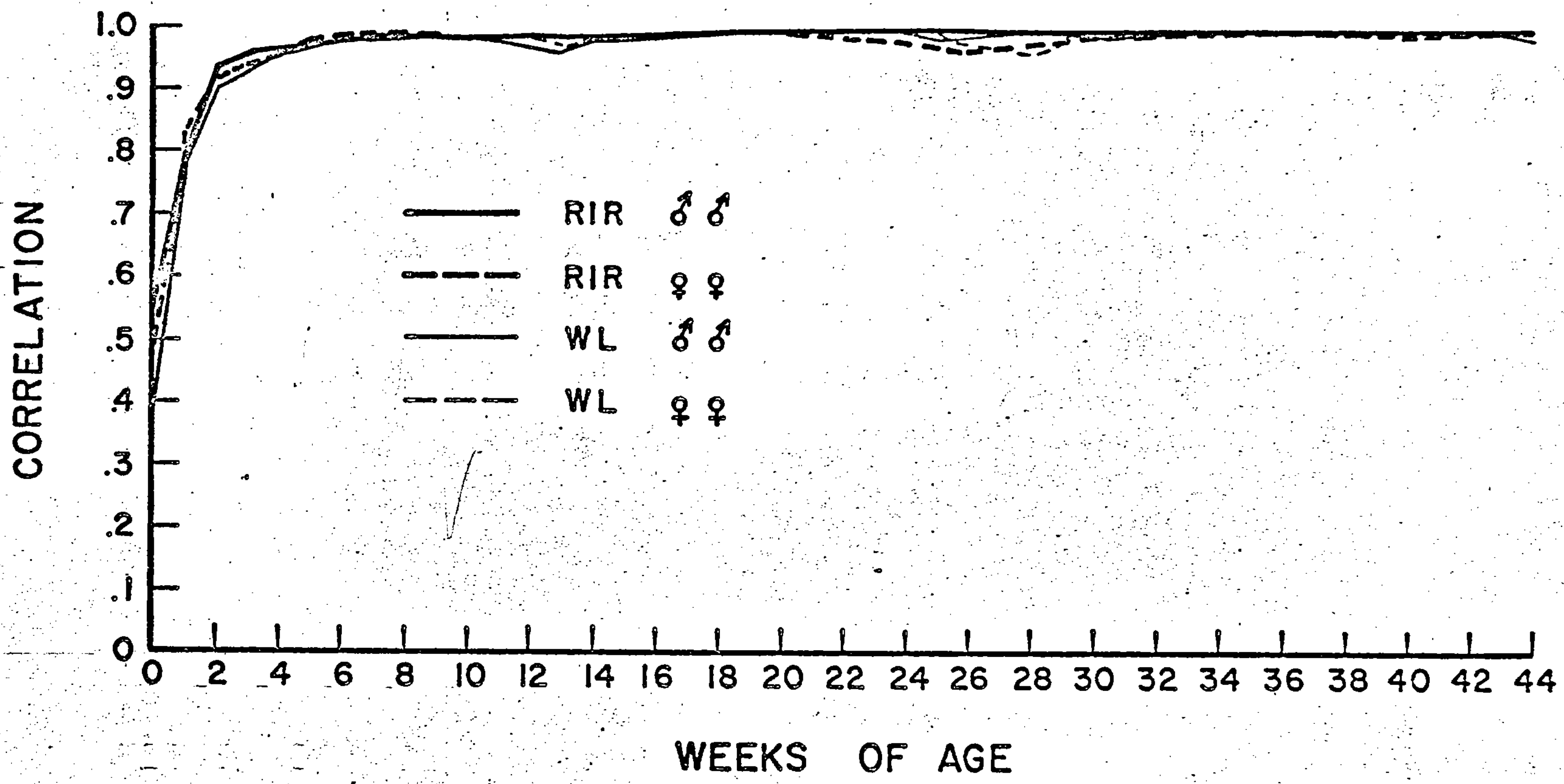


Figure 1.13. Correlations Between Consecutive Weekly Body Weights for Rhode Island Red and White Leghorn Males and Females

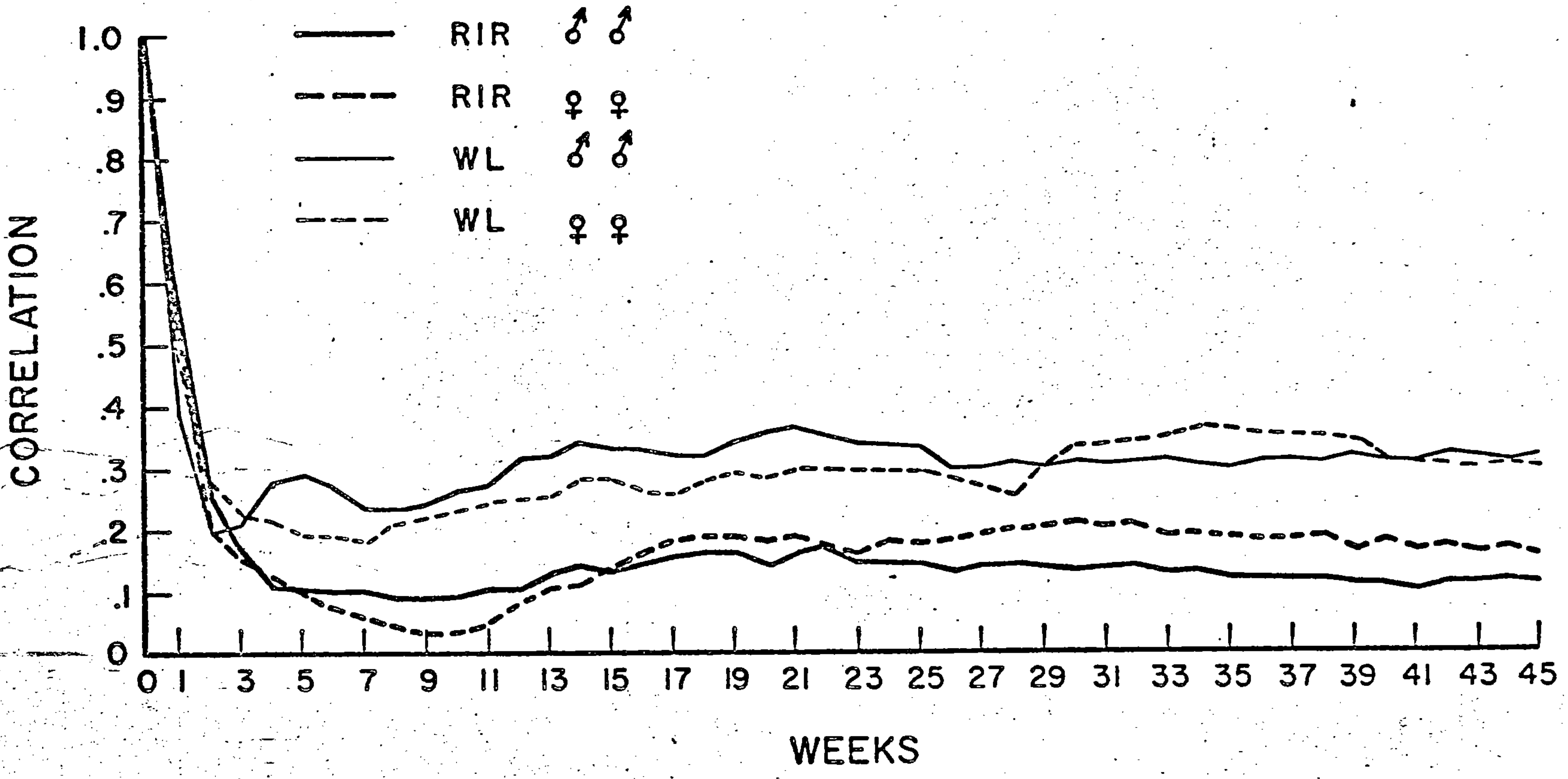


Figure 1.14. Correlations Between Initial and Successive Body Weights for Rhode Island Red and White Leghorn Males and Females

due to the diminishing influence of the hen on the chick by about three weeks of age. The relatively constant correlation thereafter indicates the continuing association between hatching weight and successive weights. This is not surprising since there is a part-whole relationship between initial and successive body weights. What is surprising, however, is that the correlations did not decrease further in later weeks. This might be expected since the hatching weight comprises a smaller proportion of the weekly weights at later ages.

Correlations Between Final and Preceding Weights. The correlations between the final body weight, at 45 weeks of age, and previous weights are presented in Table A22 and plotted in Figure 1.15 by populations. The correlations began low and generally increased over time. In the females of both lines however, there was a decline and subsequent rise in the correlations about the time they reached puberty. Again, these correlations are of the part-whole type. The overall increase in the correlation means that the weights at later ages are increasingly associated with the final weight, as might be expected.

Relationships Among Gains in Body Weight

Means and Standard Deviations

The means and standard deviations of the individual weekly gains in body weight are presented in Tables A23-A26 and plotted in Figures B5-B8 for each population.

Means of Weekly Gains in Body Weight. The means of the weekly body weight gains are plotted in Figure 1.16. The four populations followed the same general trends. Probably because of debeaking, all populations

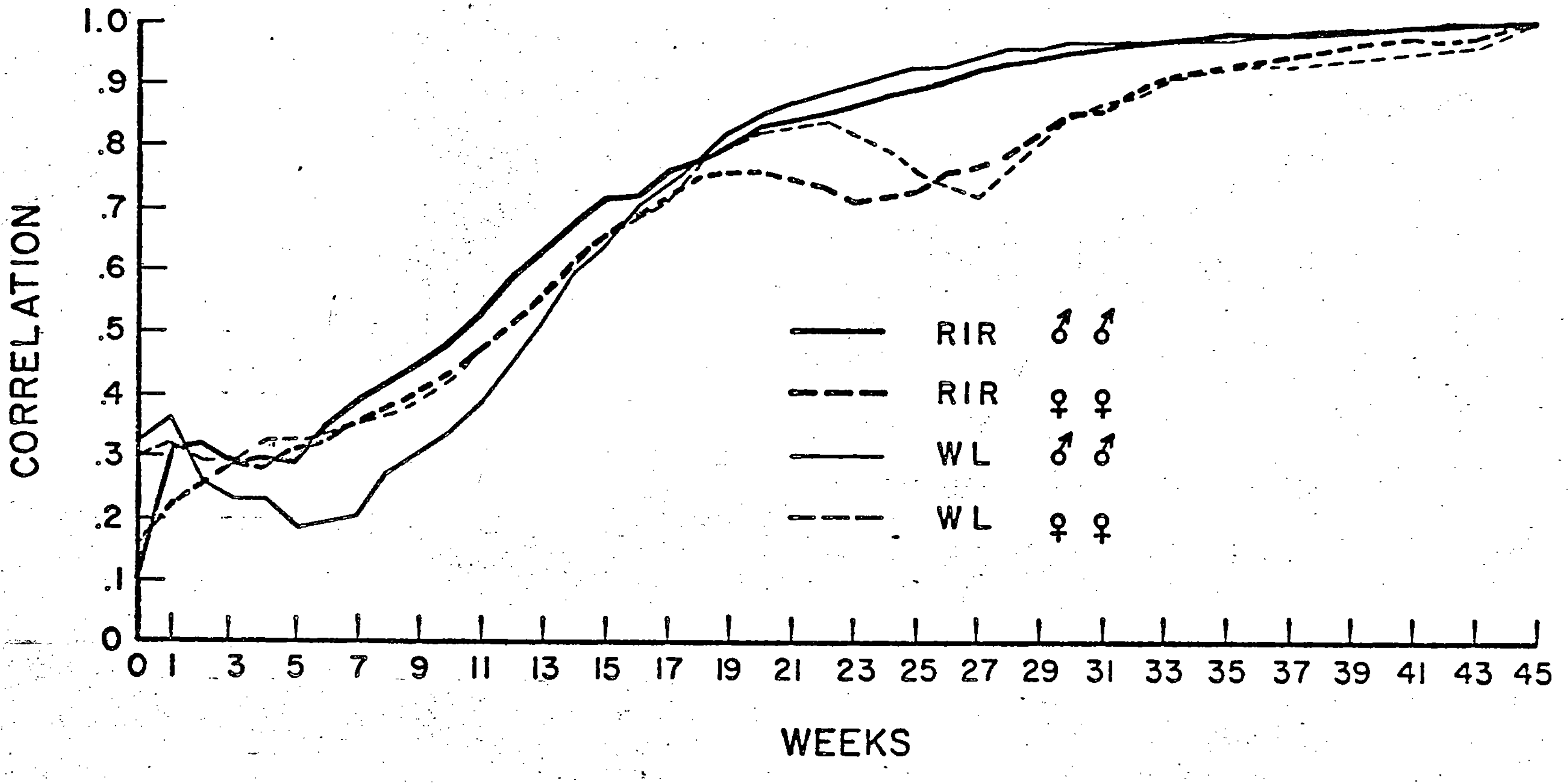


Figure 1.15. Correlations Between Final and Preceding Body Weights for Rhode Island Red and White Leghorn Males and Females

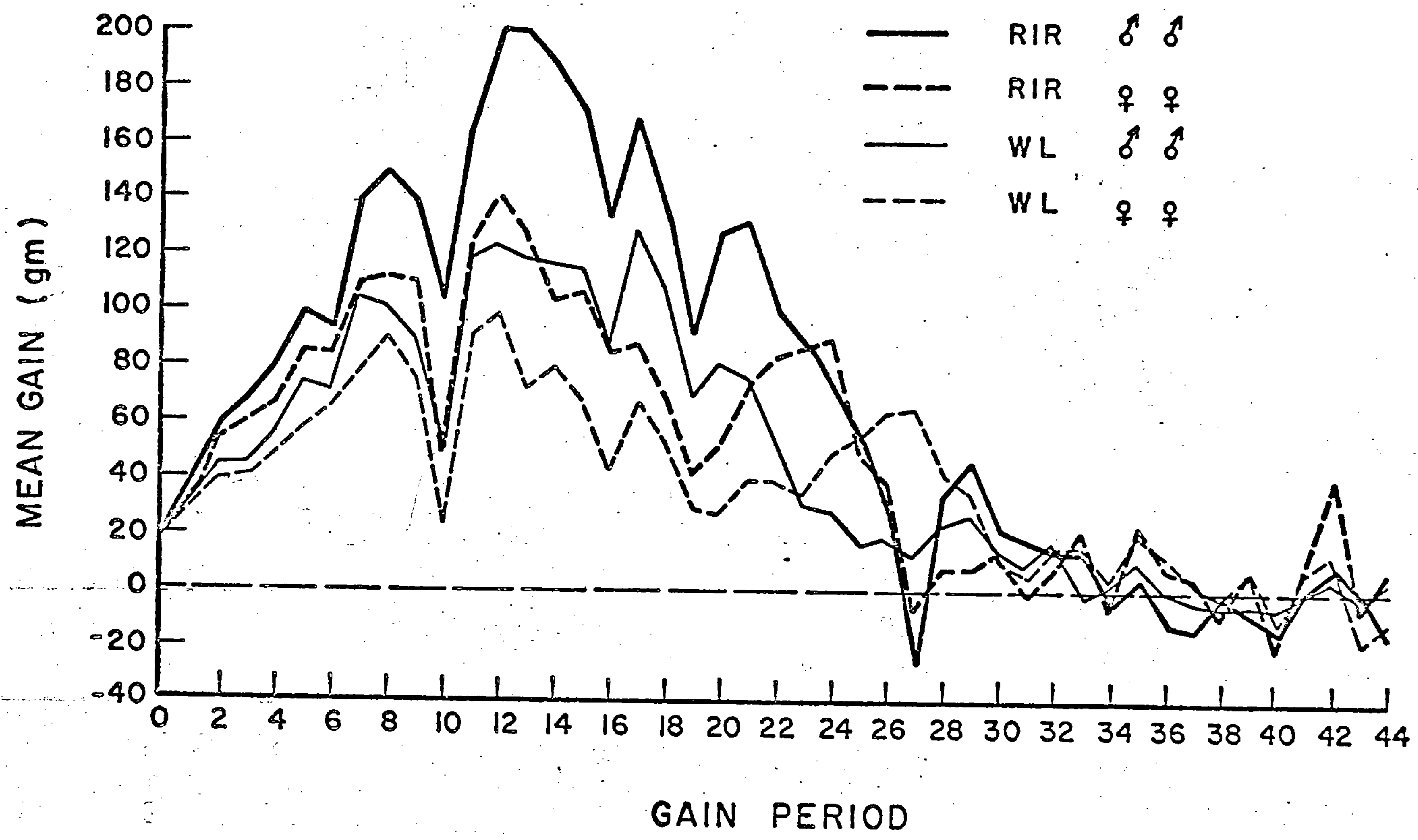


Figure 1.16. Means of Weekly Gains in Body Weight for Rhode Island Red and White Leghorn Males and Females

declined in mean gains between 10 and 11 weeks of age (gain period 10). The gains in all populations increased until 12 weeks of age and then declined. This fluctuating pattern continued with increases at 17 and 19 weeks and decreases thereafter. Towards the end of the experiment (after about 34 weeks of age) the mean gains varied around zero. This indicates that after about 34 weeks of age (perhaps earlier in the RIR line) the fluctuating gains in mean weight are mainly due to random environmental influences rather than any genetic influence to reach some final weight. This theory will be discussed further when estimates of heritability of weekly gains are examined.

Standard Deviations of Weekly Gains in Body Weight. The standard deviations of weekly body weight gains are plotted in Figure 1.17. There did not appear to be a consistently increasing trend in the standard deviations (or variance) of weekly gains in body weight as there was with weekly body weights (compare with Figure 1.2). In addition, the weekly standard deviations in gains were smaller in magnitude than the standard deviations of individual weekly body weights. It can be seen from Figures B5-B8 that the means and standard deviations of weekly gains did not consistently vary together as they did for weekly body weights (see Figures B1-B4).

Heritability Estimates of Weekly Gains in Body Weight

Weekly nested analyses of variance were performed on gains in weekly body weight. From these analyses, weekly estimates of the sire component (Table A27), dam component (Table A28) and full sib group component of variance (Table A29) were obtained. Based on these components respectively, heritabilities of gains in weekly body weight, based on the

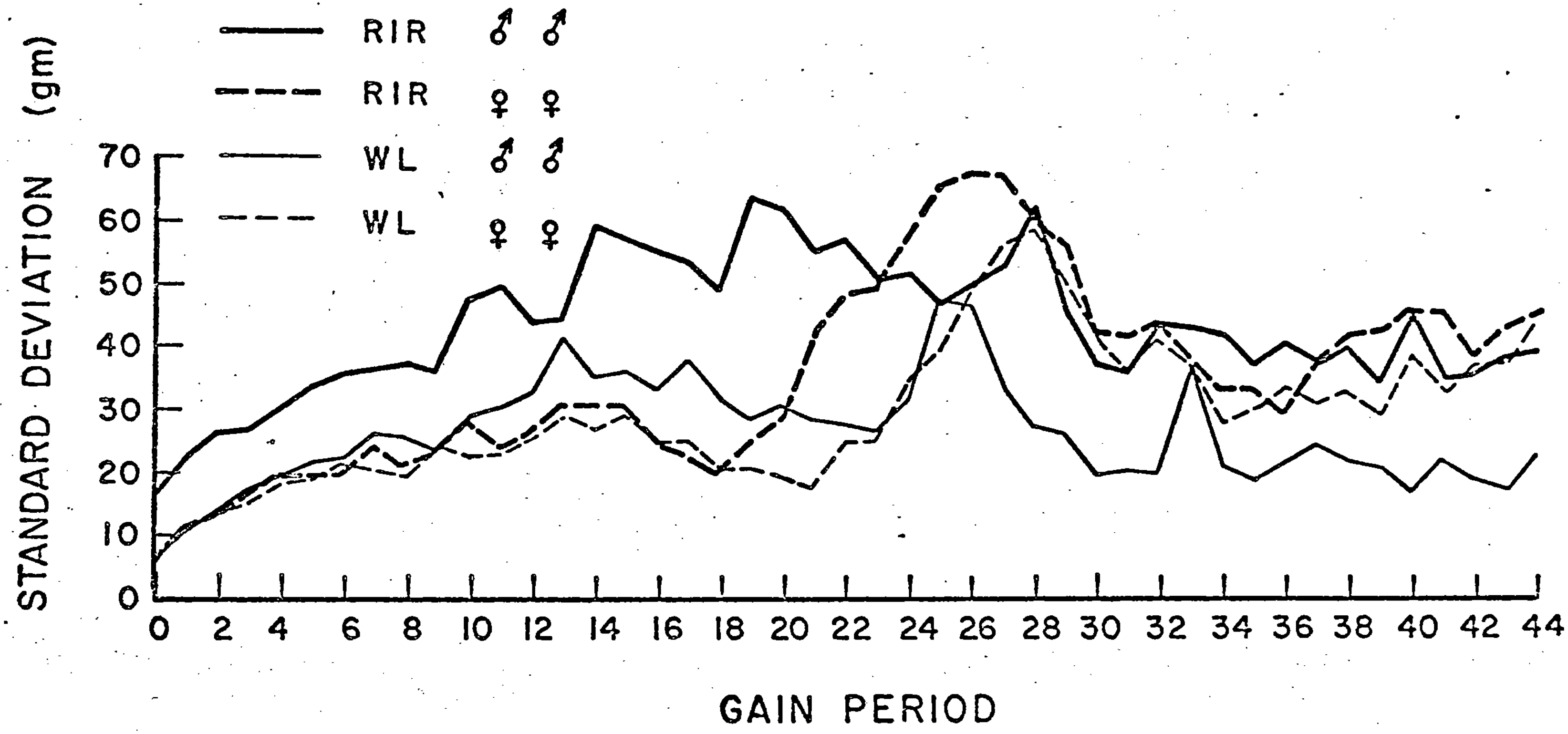


Figure 1.17. Standard Deviations of Weekly Gains in Body Weight for Rhode Island Red and White Leghorn Males and Females

paternal half sib correlation (Table A30), maternal half sib correlation (Table A31) and the correlation among full sibs (Table A32) were estimated as well as their standard errors. Figure 1.18 presents the graphs of the weekly full sib heritability estimates for each population.

The trend of the estimates over weeks was from an initial average of about 0.4 to average of about 0.1 at the conclusion of the experiment. Not only was there an apparent downward trend but the estimates were quite variable from week to week. The heritabilities appeared to vary around zero after about 31 weeks. This indicates that a large amount of the variance in weekly gains after about 31 weeks of age is probably due to random environmental variation. This is supporting evidence, along with the mean gains (see Figure 1.16), that the gains in weekly body weight after about 31-34 weeks of age are due mainly to random environmental effects rather than any genetic influence to reach a specific weight.

Average heritabilities for each population, based on the analysis of variance of weekly gains were also calculated. These estimates will be examined following the presentation of the analysis of variance of gains in weekly body weight.

Analysis of Variance of Weekly Gains in Body Weight

To examine the sources of differential effects on gains in weekly body weight, an analysis of variance was performed on weekly gains for each population. The analyses of variance are presented in Table 1.3 and the calculated coefficients of the variance components are given in Table 1.4.

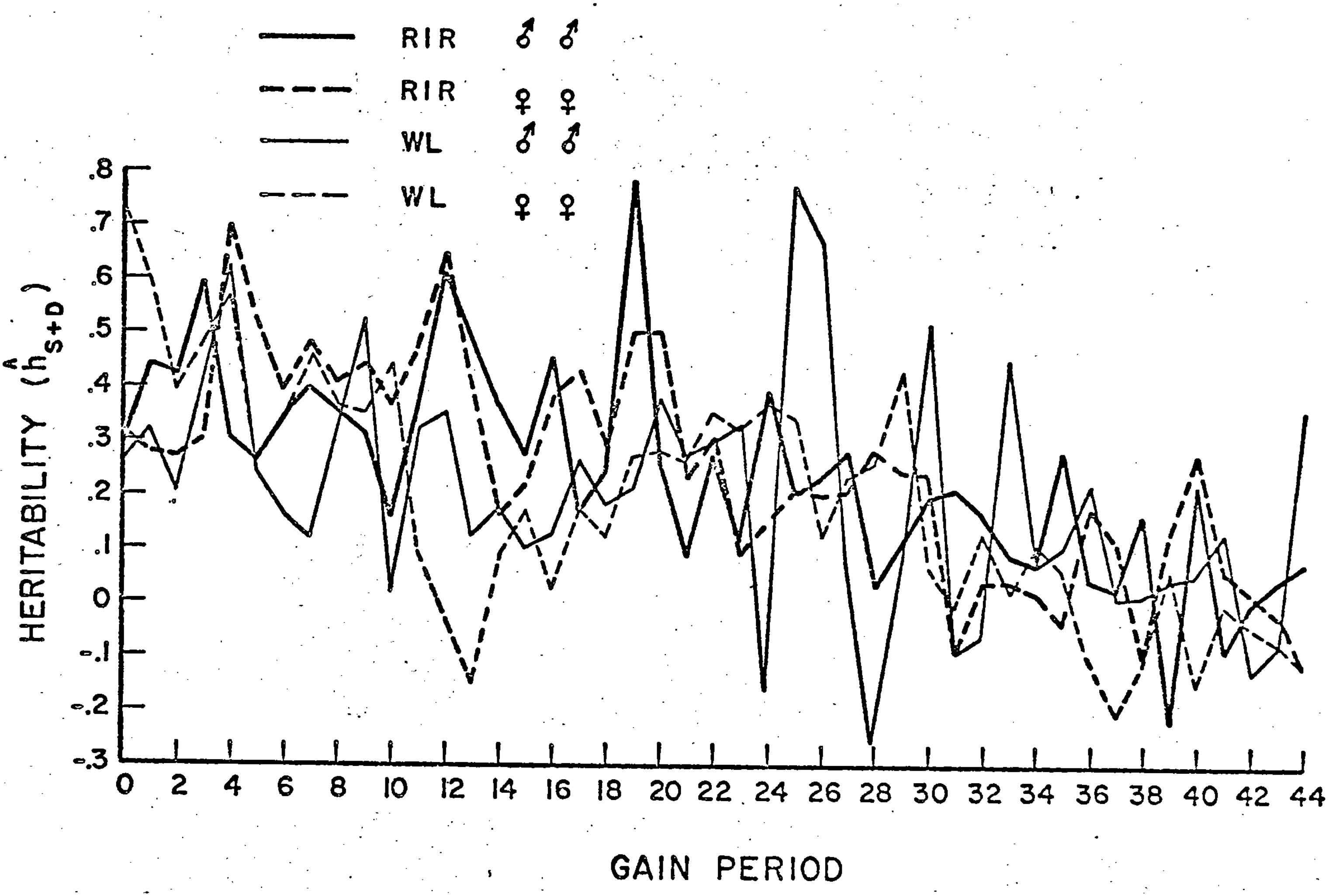


Figure 1.18. Heritability Estimates (h^2_{S+D}) of Weekly Gain in Body Weight for Rhode Island Red and White Leghorn Males and Females

Table 1.3. Analyses of Variance of Gains in Weekly Body Weight for Rhode Island Red and White Leghorn Males and Females

	RIR ♂♂		RIR ♀♀		WL ♂♂		WL ♀♀	
Source	d.f.	M.S.	d.f.	M.S.	d.f.	M.S.	d.f.	M.S.
Sires (S)	31	8,159*	31	6,240	30	2,481	33	2,344
Dams (D)/S	18	3,352*	18	3,217*	16	1,708*	17	2,701*
Progeny (P)/D/S	175	1,464	231	1,203	117	837	188	690
Weeks (W)	44	1,048,437	44	555,793*	44	318,478*	44	210,646*
W x S	1,364	1,884*	1,364	2,161*	1,320	1,004	1,452	1,436*
W x D/s	792	1,450*	792	1,883*	704	1,012*	748	982
W x P/D/S	7,700	1,103	10,164	1,432	5,148	696	8,272	990
Total	10,124		12,644		7,379		10,754	

*Approximate F-test significant at 0.05 probability level

Table 1.4. Coefficients of Variance Components in the Analyses of Variance of Gains in Weekly Body Weight for Rhode Island Red and White Leghorn Males and Females

Coefficients	RIR ♂♂	RIR ♀♀	WL ♂♂	WL ♀♀
k_1	4.576	5.512	2.997	4.506
k_2	4.442	5.663	3.730	4.762
k_3	6.951	8.690	5.246	6.958
k_4	4.938	6.238	4.159	5.259
k_5	9.524	11.619	6.634	9.393
k_6	205.902	248.014	134.839	202.758
k_7	199.889	254.839	167.848	214.286
k_8	312.787	391.037	236.049	313.100
n	225	281	164	239

Averaged over all weeks, there were significant differences among dams within sires for weekly gains, in each population. In addition, no significant differences were found among sires, except in the RIR male population. Significant week differences were found, as might be expected, but were not of particular interest.

Significant differences were found for the weeks by sires (W x S) and weeks by dams within sires (W x D/S) interactions for both sexes of the RIR line. In the WL males, only the weeks by dams within sires interaction was statistically significant, while in the WL female population just the weeks by sires interaction was real. These significant interactions indicate that the groups, either sires or dams within sires, differ in their mean gain from week to week.

From the results of the analysis of variance, estimates of the components of variance were calculated for each population (Table 1.5). The estimates of the variance components were used in estimating the average heritability and genetic correlation of weekly gains for each population.

Average Heritability of Weekly Gains in Body Weight. From the above estimates of the components of variance for sires (S), dams (D/S) and progeny (P/D/S), the average heritabilities of weekly gains were calculated for the four populations. Table 1.6 shows the three estimates of the average heritability of weekly gains by populations.

The estimates of the average heritability based on the correlation among full sibs (h^2_{S+D}) indicate a high relationship between an individual's genotype and phenotype (average of 0.74) over all populations. These results were consistent with the average of weekly

Table 1.5. Components of Variance Estimates for Weekly Gain in Weight for Rhode Island Red and White Leghorn Males and Females

Components of Variance	Population			
	RIR	RIR	WL	WL
Sires (S)	15.54*	7.59	2.37	-1.50
Dams (D)/S	9.17*	8.11*	6.46*	9.92*
Progeny (P)/D/S	32.53	26.73	18.60	15.33
W x S	64.06*	30.74*	-16.25	65.30*
W x D/S	75.82*	81.81*	105.45*	-1.78
W x P/D/S	1,102.68	1,432.07	695.50	990.01

Table 1.6. Average Heritability Estimates of Weekly Gains in Body Weight for Rhode Island Red and White Leghorn Males and Females

Population	$h_S^2 \pm$ s.e.		$h_D^2 \pm$ s.e.		$h_{S+D}^2 \pm$ s.e.	
RIR Males	1.09	.80	0.64	.38	0.86	.52
RIR Females	0.72	.46	0.76	.41	0.74	.39
WL Males	0.35	.54	0.94	.65	0.64	.58
WL Females	-.25	.59	1.67	.77	0.71	.66

estimates of heritability indicating a high repeatability of measurements across weeks. Based on the magnitude of their standard errors, however, this correspondence is probably not real. This supports the results from the weekly heritability estimates where the average heritability was low and variable across weeks (see Figure 1.18).

One might expect, therefore, not to make much predictable genetic gain when selection is based on the average weekly gains in body weight.

Genetic Correlation of Weekly Gains in Body Weight

From the estimates of the components of variance presented in Table 1.5, an average genetic correlation of weekly gain in body weight over the 45 weeks was obtained for each population. Since the statistical model was of the mixed type, the method of Yamada (1962) was used to estimate the correlations.

Robertson (1959) pointed out that the interaction component in the denominator will be overestimated if the between full sib group standard deviations (σ_{G_i}) are not equal across weeks. Therefore, the denominator was reduced by the amount of the variance among the standard deviations.

To determine the standard deviations, sire and dam components of variance were added for each week, the square root taken and the variance of these values calculated. Since the square root of a negative number could not be used, negative estimates of variance were considered as zero and included in the calculation. Therefore, the variance was underestimated but this bias was considered negligible. The weekly estimates of the full sib group standard deviations, for each population are presented in Table A33.

The variance of the weekly full sib group standard deviations was 38.81 and 28.02 for the RIR males and females, respectively. In the WL line, the variance was 39.49 and 27.88 for males and females, respectively. The estimates of the average genetic correlation of gain in body weight between any two weeks are presented below in Table 1.7 for each population.

Table 1.7. Average Genetic Correlation Estimates of Gain in Weekly Body Weight by Populations

	Line	
Sex	RIR	WL
Male	0.1761	0.1211
Female	0.1351	0.1443

It is not surprising that the average correlations were relatively low. A correlation of this type includes correlations between consecutive weeks as well as between the most distant weeks. Had the experiment been terminated earlier, perhaps when the chickens were around 30 weeks of age, a higher average genetic correlation might be expected. The reason for this is that weekly mean gains after about 31-34 weeks of age tended to be influenced, to a large extent, by random environmental fluctuations. This was noted previously when the weekly heritabilities of gains were examined and was observed again when the correlations between consecutive gains were studied.

Correlations Between Consecutive Gains in Body Weight

Presented in Table A34 and graphed in Figure 1.19 are the correlations between consecutive weekly gains in body weight for the RIR and WL males and females. There appears to be a trend over time from positive to negative correlations.

From the theory presented earlier for the correlation between consecutive gains, a positive correlation occurs when:

$$r_{W_t,W_{t+1}}\sigma_{W_t}\sigma_{W_{t+1}} + r_{W_t,W_{t-1}}\sigma_{W_{t-1}}\sigma_{W_t} > r_{W_{t-1},W_{t+1}}\sigma_{W_{t-1}}\sigma_{W_{t+1}} + \sigma^2_{W_t} \,.$$

An example of a positive correlation would be in the RIR males at week 12, i.e. correlation between gains 12 and 13. When $t = 13$,

$$r_{W_{12},W_{13}} = 0.9866;\quad r_{W_{13},W_{14}} = 0.9886;\quad r_{W_{12},W_{14}} = 0.9563$$

$$\sigma_{W_{12}} = 175.14;\quad \sigma_{W_{13}} = 191.33;\quad \sigma_{W_{14}} = 208.85.$$

Then,

$$(.9886)(191.33)(208.85) + (.9866)(175.14)(191.33)$$

$$> (.9563)(175.14)(208.85) + (191.33)^2$$

$$39{,}503.98 + 33{,}059.91 > 34{,}980.29 + 36{,}607.17$$

$$72{,}563.89 > 71{,}587.46$$

as it must for the correlation to be positive.

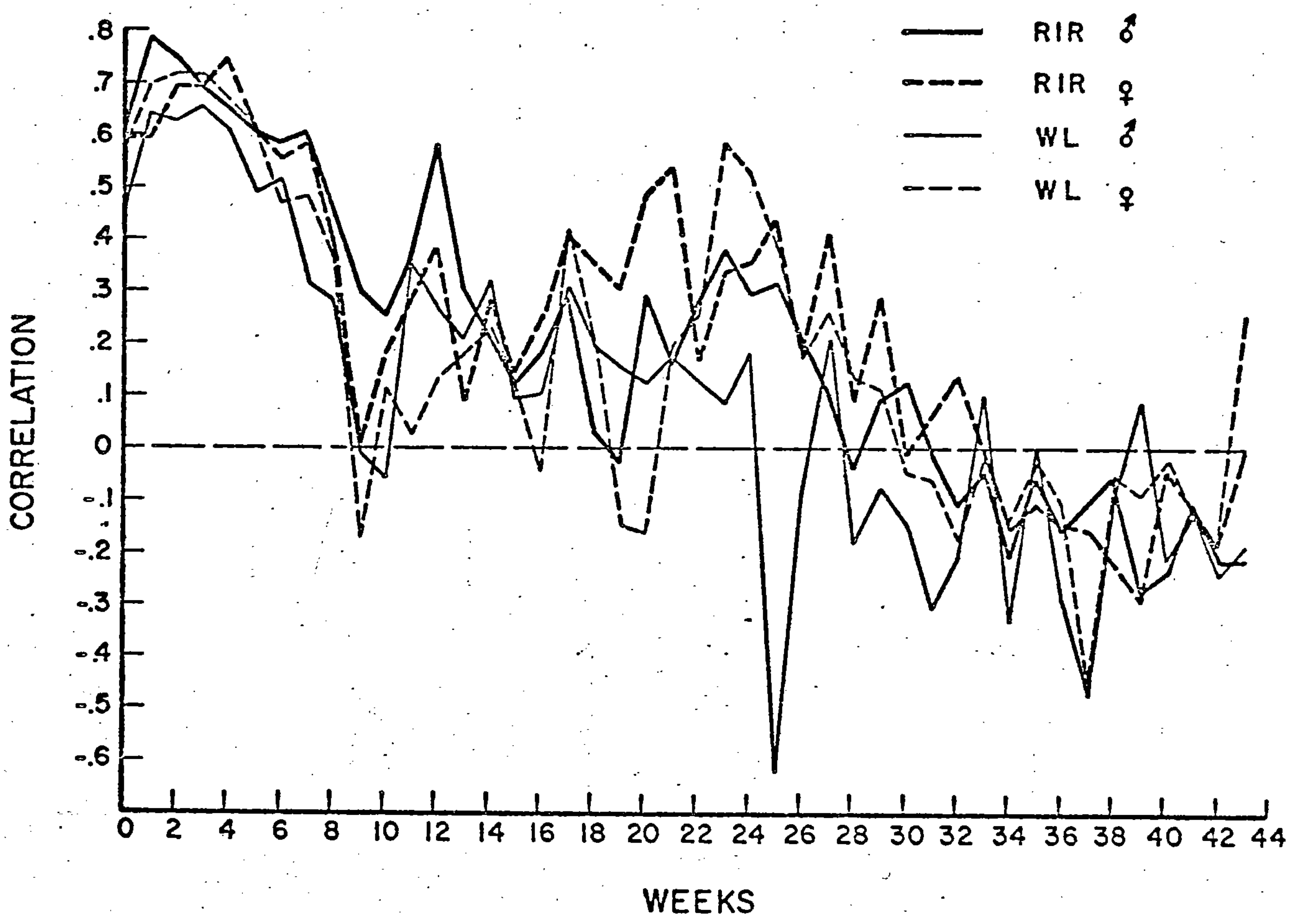


Figure 1.19. Correlations Between Consecutive Gains in Weekly Body Weight for Rhode Island Red and White Leghorn Males and Females

On the other hand, a necessary condition for a negative correlation between consecutive gains is when:

$$r_{W_t,W_{t+1}} \sigma_{W_t} \sigma_{W_{t+1}} + r_{W_t,W_{t-1}} \sigma_{W_{t-1}} \sigma_{W_t} < r_{W_{t-1},W_{t+1}} \sigma_{W_{t-1}} \sigma_{W_{t+1}} + \sigma^2_{W_t}.$$

An example of a negative correlation would be the correlation at week 25 in the WL males, i.e. correlation between gains 25 and 26. If t=26,

$$r_{W_{25},W_{26}} = 0.9786; \; r_{W_{26},W_{27}} = 0.9798; \; r_{W_{25},W_{27}} = 0.9847$$

$$\sigma_{W_{25}} = 227.22; \; \sigma_{W_{26}} = 232.72; \; \sigma_{W_{27}} = 234.77.$$

Then,

$$(.9798)(232.72)(234.77) + (.9786)(227.22)(232.72)$$

$$< (.9847)(227.22)(234.77) + (232.72)^2$$

$$53,532.26 + 51,747.62 < 52,527.44 + 54,158.60$$

$$105,279.88 < 106,686.04$$

as it must for the correlation to be negative.

Wright (1968, page 357) has explained the negative correlation in the later periods, when the average gains are small, as largely due to temporary causes. He also states that, ''These would tend to give a correlation of -0.50 between successive periods, which would be partially offset by a tendency toward positive correlation due to conditions of somewhat longer duration.'' In the example presented above, a correlation of -0.50 can be obtained only if the weights at 25, 26 and 27 weeks of age were mutually uncorrelated and the variances are equal $(\sigma^2_{W_{25}} = \sigma^2_{W_{26}} = \sigma^2_{W_{27}})$.

Relationships Between Body Weight and Gains

An important phase of this research was to develop and test the theoretical biometrical relations between body weight and gain. The theoretical development was presented in a previous section. Examples of the correlations between consecutive body weights and correlations between consecutive gains were discussed earlier. In this section the correlation between gain and subsequent weight and the correlation between weight and subsequent gain will be studied.

Correlations Between Gain and Subsequent Body Weight

Estimates of the correlation between gain in body weight and subsequent body weight for RIR and WL males and females were calculated. These estimates are presented in Table A35 and graphed in Figure 1.20.

After an increase in the correlation after hatching, the correlations generally declined; varying near zero after about week 27. The sharp decline at week 10 occurred during the period when the birds were debeaked. Of special interest are the negative correlations, for example the correlation in the WL females at week 10. From the theory presented earlier, a negative correlation occurs when the standard deviation of weights at 11 weeks of age is less than the product of the standard deviation of weights at 10 weeks and the correlation between weights at both ages. This, in fact, was the situation since from the data it can be seen that:

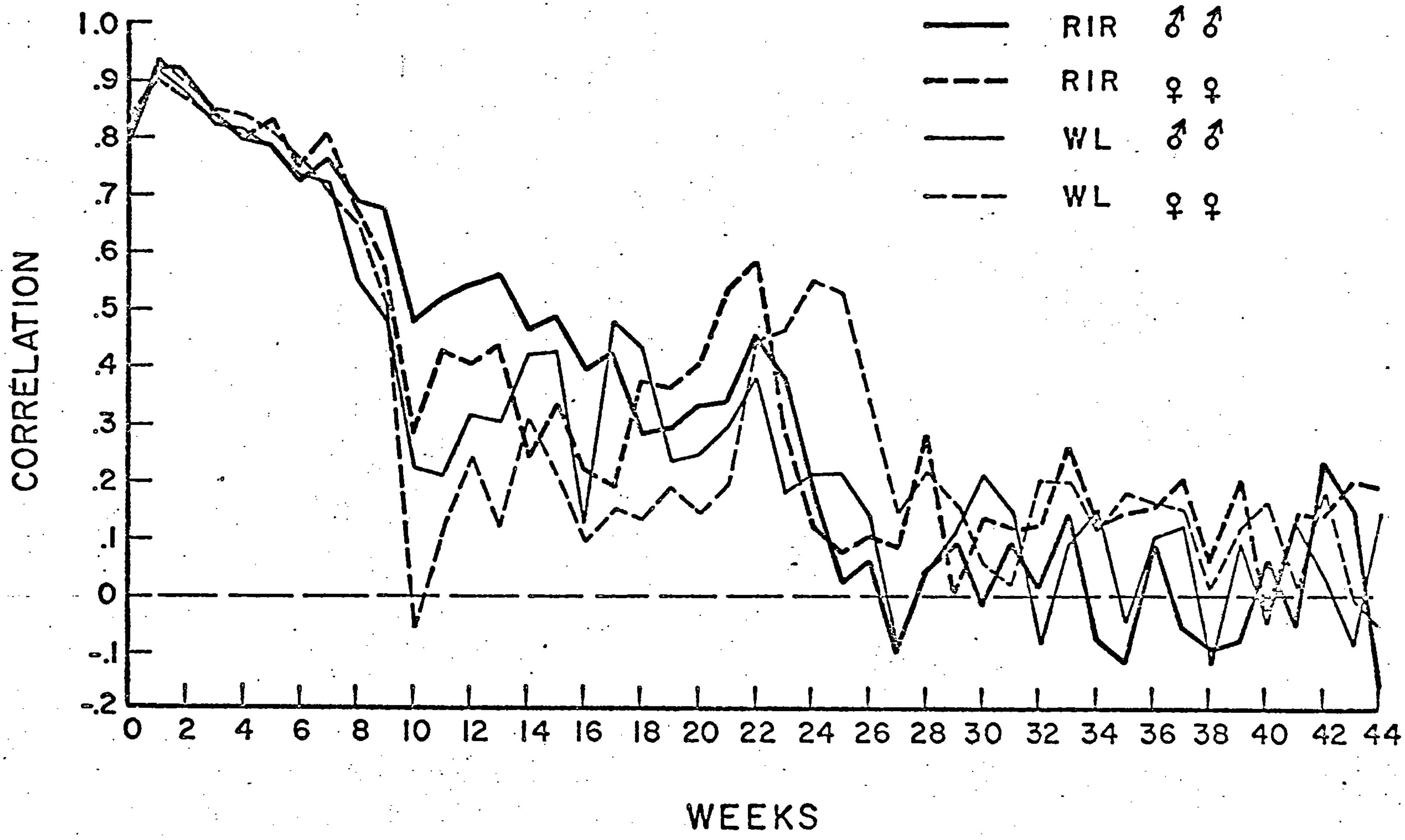


Figure 1.20. Correlations Between Gain in Body Weight and Subsequent Body Weight for Rhode Island Red and White Leghorn Males and Females

$$\sigma_{W_{11}} < r_{W_{10},W_{11}} \sigma_{W_{10}}$$

$$115.77 < (0.9816)(119.18)$$

$$115.77 < 116.99$$

The negative correlation between gain and subsequent weight means that the individuals making smaller (larger) gains between 10 and 11 weeks of age were the heavier (lighter) individuals. Thus, the individuals tended toward the same weight. This led to a reduction in the variance of body weights at 11 weeks of age as compared to the variance of body weights at 10 weeks of age (115.77 vs. 119.18).

Monteiro and Falconer (1966) have pointed out that the decrease in variance of weights, as in the above example, is indicative of compensatory growth since the heavier individuals are gaining less than the lighter individuals. It will be shown in the next section, however, that compensatory growth does not always imply a reduction in the variance.

Correlations Between Body Weight and Subsequent Gain

Estimates of the correlations between body weight and subsequent gain in body weight for RIR and WL males and females are presented in Table A36 and graphed in Figure 1.21.

The graphs showed an initial increase in the correlation from negative to positive values. This was followed by a decline in the correlations at about 10 weeks with some having negative values. The correlations increased to positive values at about the time of sexual maturity.

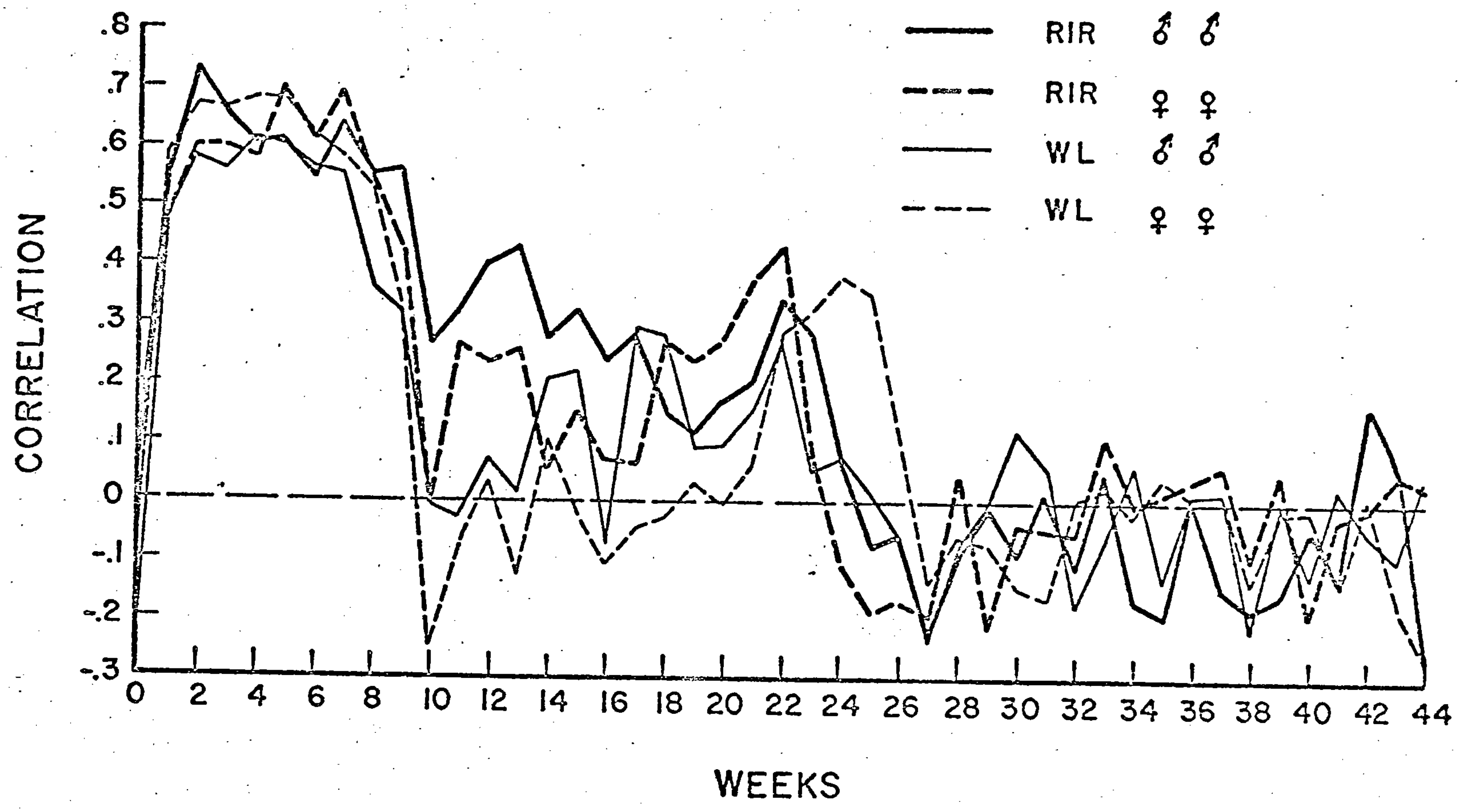


Figure 1.21. Correlations Between Body Weight and Subsequent Gain in Body Weight for Rhode Island Red and White Leghorn Males and Females

This would indicate that the larger individuals had a larger gain at this time. The high correlation in the females, at this time, could be explained by a larger (smaller) increase in the size of the ovary in larger (smaller) females. After the time of sexual maturity, the correlations in all populations were negative and leveled off around or a little below zero after about 27 weeks of age.

As the theory dictates, a negative correlation between body weight and gain to the subsequent body weight occurs when the product of the correlation between the consecutive weights and of the standard deviation of the succeeding weight is less than the standard deviation of the preceding weight . An example of this negative correlation is in the WL males, between hatching weight and gain to one week of age ($r= -.2381$). From the data it can be seen that, when $t = 1$,

$$r_{W_0,W_1} \sigma_{W_1} < \sigma_{W_0}$$

$$(0.4734)(6.68) < 3.99$$

$$3.16 < 3.99$$

which is necessary for the correlation to be negative.

The negative correlation indicates that lighter (heavier) individuals gain more (less) which implies some compensatory growth. Note that the negative correlation is not brought about by a decrease in variance of weights, since $(6.68)^2 > (3.99)^2$, but is caused by a relatively low correlation between the first two weights. This low correlation is indicative of the maternal influences on the chicks. Thus, compensatory growth is <u>not always</u> accompanied by a decrease in variance. This is only true when the correlation between consecutive weights is one. Therefore, the definition of compensatory growth does not necessarily imply a reduction in the variation of body weight but rather a negative correlation either between body weight and subsequent gain or gain and subsequent body weight.

SUMMARY AND CONCLUSIONS

Considerable research has been carried out on body measurements of chickens, especially in the study of the change of body weight at a specific time over several generations. Some work has also been done on the change of body weight during specific periods of time. There is a dearth of information, however, regarding the relationship among and within weekly body weights and weekly gains over an extended period in an individual's lifetime. Therefore, it was the purpose of this research to study the heritabilities of weekly body weights and gains over a period of almost one year. In addition, the theoretical correlations between consecutive weights, consecutive gains, weight and subsequent gain, as well as gain and subsequent weight were derived under varying assumptions. The theoretical results were compared to empirical results.

Estimates of heritabilities and correlations were based on measurements taken on weekly body weights of 909 chickens of both sexes from two random mating control lines, the Rhode Island Red (RIR) and White Leghorn (WL), from hatching to 45 weeks of age. Gain in weekly body weight was defined as the difference between two consecutive weekly body weights on the same individual. The individuals in the four populations were maintained under similar conditions, as much as possible, in order to reduce environmental differences among the individuals.

Menas and standard deviations of weekly body weights were estimated. A direct relationship between the change in the mean and the change in the variance suggested that the coefficients of variation should also be studied. Both phenotypic and genetic coefficients of variation (the latter is a ratio of the square root of the additive genetic variance to the phenotypic mean) were examined over weeks. The phenotypic coefficients of variation for weekly body weights showed an increase to a maximum at about three to six weeks of age with a subsequent decline until the values leveled off from about 15 weeks of age at about 12 to 13 per- The genetic coefficients of variation, on the other hand, showed an initial decrease until two weeks of age, perhaps an indication of nongenetic influences, with a subsequent increase to a maximum at between four to six weeks of age. Then, after a decline, it leveled off at a value between 9 and 11 percent.

Weekly nested analyses of variance were performed on body weights in order to obtain weekly heritability estimates in all populations. The initial heritability estimate was greater than one in all populations. After a decline to a value of 0.4 to 0.7 the heritability estimates started to increase. At the conclusion of the experiment the heritability estimates were 0.86 and 0.66 for the males with estimates of 0.74 and 0.72 for the females of the RIR and WL lines, respectively.

With special reference to the weekly estimates of the sire component of variance in the RIR female population, the sire components were consistently negative from one to eight weeks of age and positive thereafter. A possible explanation in terms of a negative estimate of the phenotypic correlation between half sibs was proposed. This negative estimate probably was brought about by competition for food and social interaction among half sibs.

The correlations between consecutive weights were also calculated. These correlations are representative of a relationship known as part-whole, since the weight at some previous time is part of the whole weight at a later time. The correlations, in all populations, rose until about six or seven weeks and leveled off at almost one thereafter. The correlations between initial and successive weights declined until about two or three weeks of age and then remained steady at about 0.30 for the WL line and about 0.15 for the RIR line. The relatively constant correlation indicated the low continuing association between hatching weight and successive weights. The correlations between the final body weight and previous weights, however, began low and generally increased over time. The overall increase in the correlation meant that the weights at later ages were increasingly associated with the final weight, as might be expected in correlations of the part-whole type.

The means and standard deviations of the individual weekly gains in body weight were estimated. The four populations tended to increase until about 12 weeks of age and generally declined thereafter. Towards the end of the experiment the mean gains varied around zero, probably due mainly to random environmental influences. The means and standard deviations of weekly gains did not consistently vary together as they did for weekly body weights.

In order to obtain heritability estimates of weekly gains in body weight, weekly nested analyses of variance were performed for each population. The trend of the estimates, based on the correlation among full sibs, was apparently downward, but the estimates were quite variable from week to week. After about 31 weeks, the heritabilities appeared to vary around zero, indicating that a large amount of the variance in weekly gains after that period was probably due to random environmental variation.

An analysis of variance, over all weeks, was performed on weekly gains for each population. Averaged over all weeks, there were significant differences among dams for weekly gains, in each population. No significant differences were found among sires, except in the RIR male population.

Significant differences were found for the weeks by sires and weeks by dams within sires interactions for both sexes of the RIR line. In the WL males, only the weeks by dams within sires interaction was statistically significant, while in the WL female population just the weeks by sires interaction was significant. These significant interactions indicate that the groups, either sires or dams within sires, differed in their mean gain from week to week.

From the estimates of the components of variance of the analysis of variance of weekly gains, average heritability estimates of gains over weeks were calculated. The estimates of the average heritability, based on the correlation among full sibs, were high (average of 0.74) but probably not significantly different from zero considering the magnitude of the standard error. One might not expect, therefore, to make a predictable genetic gain when selection is based on the average weekly gains in body weight.

An average genetic correlation of weekly gain was estimated based on the full sib components of variance. The estimate of the correlation was adjusted for the variance among full sib group standard deviations from week to week. The average correlation ranged from 0.12 to 0.18 in the four populations. The correlations were low, in part, because this type of average correlation included correlations between consecutive weeks as well as between the most distant weeks.

The correlations between consecutive weekly gains were also studied in the RIR and WL males and females. There was a trend over time from positive to negative correlations. The theoretical expectations of the correlations were examined to determine the conditions under which the correlation would be positive or negative. The results were corroborated experimentally.

Finally, to study the relationship between body weights and gains, the correlation between gain and subsequent body weight and the correlation between body weight and subsequent gain were examined. It was of particular interest to consider when these correlations were negative since that would indicate compensatory growth. It had been thought that compensatory growth implied a decrease in the variance of body weights. The theoretical results showed compensatory growth did not necessarily imply a decrease in the variance since the negative correlation was also a function of the correlation between consecutive weights. It was confirmed empirically that, with a sufficiently small correlation between consecutive weights, a negative correlation between weight and the subsequent gain would not yield a decrease in the variance of weights.

RECOMMENDATIONS

In animal production, certain growth patterns are more desirable than others, often for economic reasons. Therefore, some consideration should be given to developing different shaped growth curves.

Recently, Tallis (1968) suggested applying selection pressure at different discrete points in the growth curve of an individual in order to change the shape of the curve. He proposed to develop an optimum growth curve by constructing a linear selection index based on body weights at different ages. He also discussed a selection index which would exert selection pressure to all points of the curve simultaneously.

When one attempts to change the shape of the growth curve one must take into account the biometrical relationships among body weights and gains. In poultry for example, it is often desired to breed for an individual with early gains and a small mature weight. Tallis' approach suggests selecting up on early weights and down on later weights in the form of an index. In the light of the theoretical relations developed here among weights and gains perhaps another approach may be useful. We know that body weights at different times on the curve have a part-whole relationship and are positively correlated. Therefore, selecting up on early weights would tend to raise later weights unless sufficient downward selection pressure is placed on those later weights. As an alternative method we might select up on early weights and down on gain between early and mature weights. A necessary condition for efficient selection then would be to have a negative correlation between early weight and subsequent gain (the heavier individuals gaining less) or a positive correlation between gain and mature weight (those making a smaller gain would be lighter). If either of these conditions do not hold, then alternative selection criteria should be explored. The significance of studying the relationship among body weights and gains as well as how and why the components of the relations change with different shaped growth curves can certainly be appreciated. This approach is not only of theoretical interest but also justified practically. An experimental test of the theory by selection for an optimum growth curve would be highly recommended.

As a consequence of some of the results of this study, it would not be recommended, under the conditions used in this experiment, that the growth curve be considered beyond about 34 weeks of age. Based on the estimates of weekly heritabilities of body weights as well as the correlations between consecutive gains it appears that a considerable amount of the variation of weekly body weights after that age was nongenetic in origin. It would be reasonable to assume these variations were due to fluctuations in the environment. A possibility would be to conduct the selection experiment for an optimum growth curve under a controlled environment but this may prove impractical with poultry.

Another approach to selection for changing the growth pattern would be to determine a nonlinear mathematical function which best describes the growth curve of the individual. This function could be developed from an equation which relates the rate of gain to the weight of an individual and the gain to be made through a proportionality or growth rate constant. Possibly then, an optimum growth curve could be developed by changing the growth rate constant along with the other parameters in the mathematical function. It is this nonlinear approach that was studied in another phase of this research. The results of that study will be reported in Chapter II on Growth Rates and Growth Functions.

CHAPTER II. GROWTH RATES AND GROWTH FUNCTIONS

LITERATURE REVIEW

Growth can be defined as, "... the net balance of mass produced and retained (incremental component) over mass destroyed and otherwise lost (decremental component)..." (Weiss and Kavanau, 1957). Growth has been correlated with different measurements on several biological levels. For example, on the biochemical level, RNA and DNA content have been measured in Drosophila (Church and Robertson, 1966) to determine genetic differences in growth. At the tissue and organ levels, protein metabolic activity in skeletal muscle has been physiologically related to body size in mice at two ages (Gall et al. 1967). In the organism, parameters of growth regulation have been studied using differential equations to express the relationships among the components of growth of the chicken (Kavanau, 1961). A common approach at the population level is the study of the genetic and biometrical properties of the overall pattern of growth. From a biometrical study the parameters of a mathematical growth function can be determined which uniquely describe the growth curve of each individual in the population and therefore the population.

Growth Rates

Among the parameters of several growth functions is one called the intrinsic growth rate constant. The intrinsic growth rate is distinct from the average rate of change in body weight. To obtain a better understanding of the meaning of this growth rate constant, several of the commonly used growth rate estimators will be discussed and examples of each will be presented.

Absolute Rate

The absolute growth rate or rate of gain is the ratio of the difference in observed weight to the corresponding time difference. When the weights are the limits of the range of weights this represents an average absolute rate of gain. The absolute growth rate, however, gives no idea of the rate of gain between any given times (x), and is represented by the equation: $\Delta W / \Delta x = (W_{max} - W_o) / (x_{max} - x_o)$. Lerner and Asmundson (1938) used a variation of this equation to study the growth rate in chickens.

Instantaneous Absolute Rate

The shorter the interval of time for which the average absolute rate of gain is computed $(\Delta x \rightarrow 0)$, the closer it approaches the differential, dW_x. The instantaneous absolute growth rate is the ratio of the differentials or the derivative, dW_x / dx.

Relative Rate

The relative growth rate is represented by the ratio of the gain in weight during a given unit of time to the average weight of the organism during the time period. When the weight gain is great relative to the body weight, an average relative growth rate is more appropriate and can be expressed by the formula: $(W_{max} - W_o) / \frac{1}{2}(W_{max} + W_o)$. Brody

(1945) points out that this formula is unsatisfactory since the denominator, "... is obtained on the assumption that the growth rate [rate of gain] occurs in a linear manner, which in practice is true only for short intervals."

Instantaneous Relative Rate

In place of the average relative growth rate, the instantaneous relative growth rate may be used to consider short intervals. The instantaneous relative growth rate is represented by the ratio of the instantaneous weight gain relative to the weight at the time of the gain, $(dW_x \;/\; dx) \;/\; W_x$. Since it is impossible to measure the instantaneous relative growth rate, techniques from the calculus have to be utilized to consider the integrated or cumulative weight function. Baker (1944) adopted a form of the instantaneous relative growth rate for work in chickens.

Intrinsic Rate

An extension of the instantaneous relative growth rate is what shall arbitrarily be called the intrinsic growth rate constant. This is analogous to the instantaneous relative growth rate. However, an intrinsic growth rate is relative to not just the weight at a given time (W_x) but also to the gain yet to be made (ΔW_x). The intrinsic growth rate constant (<u>k</u>) may be expressed as some function of the weight at a given time and the potential for gain:

$$k = \frac{dW_x \;/\; dx}{f(W_x, \Delta W_x)}$$

where ΔW_x may be considered the gain yet to be made to some maximum weight within the period of the experiment. The logistic function is an example of the use of an intrinsic growth rate in a growth function.

Because an intrinsic growth rate constant is a function of both the weight at a specific time and the gain to maximum weight it was felt that this constant would be a meaningful growth rate when considering the entire growth curve. Therefore, it is the intrinsic growth rate constant with which we shall concern ourselves in formulating a mathematical function for the growth curve of chickens.

Growth Functions

Many types of growth functions have been used to characterize the growth curve of individuals and populations. These functions relate weight at a given time to different terms through the growth rates described above. For example the weight at a given time may be related to time alone, weight at a specific time, the gain to be made, or both the weight at a particular time and the gain yet to be made. The development of several growth functions from their growth rate equations will be discussed and examples of their use will be presented.

Polynomial Function

In attempting to represent a time trend of p repeated observations, as in the growth curve of an individual, a simple approach is the construction of a polynomial of degree $n \leq p$ in terms of the time element, x. Brody (1945) cites the work of Pearl and Reed (1923) who presented their equation in terms of rate of gain as:

$$\frac{dW_x}{dx} = k_1x + k_2x^2 + k_3x^3 + \ldots + k_nx^n \quad ,$$

where the <u>k</u>'s are unknown coefficients.

Wishart (1938) compared individual weight curves, fitted by the least squares method, to a second degree polynomial. He then analyzed the coefficients of the linear and quadratic terms to test the effect of treatments on the growth curves. The assumptions, of course, were that the weights were linearly related to time, uncorrelated and had the same variance. The emphasis was not on obtaining a model which biologically described growth but on determining differences between groups of growth curves. Rao (1958) continued this approach by using differences between consecutive weights as the dependent variable and regressing this variable on the time interval. The regression coefficient provided an estimate of the rate of gain. He also suggested a multiple regression procedure using gain as the dependent variable and where the regression coefficients were a function of time.

When the <u>p</u> observations are made at equally spaced intervals, one can easily use orthogonal polynomials or repeated differences to fit the data (Hills, 1968). Although polynomials are convenient mathematically, just goodness of fit alone is not sufficient justification for using the function. This method of representing the data does nothing more than relate weight to a function of time. A function of time alone has no biological interpretation, since it gives no insight into the process of growth at any level of the organism.

The following example makes use of the time function in work with chickens. Roberts (1964) used a special case of the polynomial, a simple power function in time, to fit a linear portion of the early growth curve, from hatching to seven weeks of age. He estimated the exponent of a function in the form, $W_x = ax^k$, where W_x is the weight at time $\underline{x}$, $\underline{a}$ is the initial weight (when $x = 1$ and not $x = 0$ as stated by Roberts) and $\underline{k}$ is the early growth rate. His method was to take ratios of consecutive weights and solve for weekly $\underline{k}$'s in each individual using the equation:

$$k = \log\left(\frac{W_2}{W_1}\right) / \log\left(\frac{x_2}{x_1}\right),$$

for example, between the first two weights.

His average values for $\underline{k}$, in four different lines, over the seven weeks showed significant differences between lines and sexes when the data were subjected to an analysis of variance.

Although Roberts conveniently makes the statement that the variable, early growth rate, meets all the assumptions necessary for statistical tests of significance, the validity of assuming normality of a ratio of logarithms is open to question. In addition, Roberts' curve has the point of inflection when $x = 0$. It is known from experimental data, however, that the growth pattern of chickens is S-shaped or sigmoid and has an inflection point at $x > 0$. Nevertheless, his procedure could be used if, under certain environmental conditions (for example a high protein diet), the observed curve had an inflection point close to or at zero.

Using the same time function, $W_x = ax^k$, Tanabe and Saeki (1964), working in Japan with pure and crossbred chickens from hatching to ten weeks of age, estimated values for k for each sex, based on the log transformed function, $\log W_x = \log a + k \log x$. In both the pure and crossbred lines the males had a higher k value than the females in the same breed. Thus, consistent with Roberts' work, sex differences were found, but the k values were not the same as in Roberts' experiment since a different range of time was used and different breeds were studied.

Exponential Function

Brody (1945) recognized that the general shape of the entire weight curve was determined by two opposing forces: a "growth-accelerating force" which allowed a constant rate of increase in reproducing units, indefinitely; and a "growth-retarding force" which allowed the increase in units to be proportional to the available limited resources.

He divided the growth curve into two segments, the first part with an increasing slope he called the "self-accelerating phase of growth" and the second part with a decreasing slope he called the "self-inhibiting phase of growth". The point of division was to be the point of inflection in the age curve, To Brody, the point of inflection represented more than the time of maximum gains; it indicated the age of puberty, the lowest specific mortality (i.e., the ratio of the number dying to the number living of the same age) and a reference point for the determination of equivalence of age in different animals.

The Self-accelerating Phase of Growth. Brody used the exponential function on the self-accelerating phase of growth, when the slope of the curve was increasing. His premise was that during the early stages of growth the rate of gain is proportional to the weight of the individual at a given time. The function he used to describe the instantaneous growth rate was:

$$\frac{dW_x}{dx} = kW_x \tag{2.1}$$

where k is the proportionality or growth rate constant, and W_x is the weight of the animal at time x.

Rearranging equation (2.1) and then integrating, with respect to time, from t' to t, he obtained:

$$\frac{dW_x}{W_x} = kdx$$

$$\int_{t'}^{t} \frac{dW_x}{W_x} = k\int_{t'}^{t} dx$$

$$\ell nW_t - \ell nW_{t'} = k(t-t')$$

$$\ell nW_t = \ell nW_{t'} + k(t-t') \tag{2.2}$$

where: ℓn indicates the natural logarithm, and $W_{t'}$ is the weight at some initial time, or the initial weight. When taking the antilog of equation (2.2), he obtained:

$$W_t = W_{t'}\, e^{k(t-t')} \tag{2.3}$$

where e is the base of the natural logarithms.

Brody estimated the growth rate constant (k) from a least square regression analysis using equation (2.2). Using data from White Rock chickens measured up to 12 weeks of age, Brody found that the growth rate constant (k) during the first four weeks was different from the constant estimated for the remaining weeks. He reported two values for k since there appeared to be a break in the curve at about three to four weeks of age (Brody, 1945, page 523).

Brant (1951) studied early growth rate (from 1 to 12 weeks of age) in a total of 395 chickens of both sexes from two pure and crossbred lines. He estimated the growth rate constant (k) by a least square regression analysis on the common log transformation of equation (2.3). He found significant differences between sexes for the constant (k) in each of the four breed groups, although in each of the three hatches, not all groups showed significance. The least variable breed was the Rhode Island Red and the male was the least variable sex.

The function in equation (2.3) is monotonic increasing with time and without an inflection point in the observed range indicating unlimited growth. It is well known, however, that chickens have limited growth; their growth pattern being S-shaped or sigmoid and having a point of inflection. Thus, the function for the self-accelerating phase of growth alone does not describe the entire growth pattern very well.

The Self-inhibiting Phase of Growth. Brody also used an exponential function on the self-inhibiting phase of growth, when the slope of the curve was decreasing. The formulation was based on the tendency for growth to be limited and the rate of gain to be proportional to the amount of growth to be made in order to reach the maximum weight, $(W_\infty - W_x)$. The function used to describe the instantaneous growth rate was:

$$\frac{dW_x}{dx} = -k'(W_\infty - W_x) \tag{2.4}$$

where k' is the growth rate constant and W_∞ is the maximum weight.

Rearranging equation (2.4) and integrating with respect to time, from t' to t, he obtained:

$$\frac{dW_x}{(W_\infty - W_x)} = -k' \, dx$$

$$\int_{t'}^{t} \frac{dW_x}{(W_\infty - W_x)} = -k' \int_{t'}^{t} dx$$

$$-\ln(W_\infty - W_t) = -\ln(W_\infty - W_{t'}) - k'(t-t') \quad . \tag{2.5}$$

Taking the antilog of equation (2.5), he obtained:

$$-W_\infty + W_t = -(W_\infty - W_{t'})\, e^{-k'(t-t')}$$

$$W_t = W_\infty - (W_\infty - W_{t'})\, e^{-k'(t-t')} \quad . \tag{2.6}$$

To summarize, Brody (1945) defines two independent growth curves. One is based on the tendency that the instantaneous rate of gain, prior to puberty or the point of inflection, is proportional to the growth already made, and is described by the equation:

$$\frac{dW_x}{dx} = kW_x$$

$$W_t = W_o \, e^{kt}, \quad \text{when } t' \text{ equals zero.}$$

Following puberty the rate of gain tends to be proportional to the gain yet to be made and is described by the second equation:

$$\frac{dW_x}{dx} = -k'(W_\infty - W_x)$$

$$W_t = W_\infty - (W_\infty - W_o)e^{-k't}, \quad \text{when } \underline{t'} \text{ equals zero.}$$

Criticism of Brody's development has centered around his reasons for dividing the total growth curve into two segments at the inflection point. In a discussion following a paper presented by E. B. Wilson (1934) skepticism was expressed about "... the validity of postulating discontinuities ... when the results are plotted on some special kind of graph paper". He went on to say that, "What makes the discontinuities is usually the observer's insistence that the underlying process be exponential, and not any marked discontinuity in the position of the experimental points"!

Brody's basis for using the inflection point as the point of discontinuity was that it coincided with the age of puberty. It is known, however, that in chickens, the point of inflection occurs at about 12-14 weeks of age (1/3 of the time to mature first year weight) whereas the age of sexual maturity is about 20 weeks of age.

Brody defends his position by stating only that, "When external conditions are equal, growth exhibits general statistical continuity in its path toward a certain equilibrium, but within this general continuity there appear to be detailed discontinuities". He cites supportive evidence that, "... relative discontinuities in the growth curve... are generally known". The objection to his development may not be so much the fact that the total growth curve was partitioned into divisions but the arbitrariness with which it was done. As Israelsohn (1960) pointed out, the division of the curve into cycles carries with it the risk of wrong division.

Another point of criticism, perhaps as a consequence of the previous remarks, is that $\underline{k}$ is not necessarily equal to $\underline{k}'$. This in itself is not the serious weak point since the growth rate may be a constant during a given time interval and may change during the interval of the total growth curve. However, the estimated value for the growth rate depends on the growth cycle chosen, and just as divisions of the growth curve are arbitrary, so are the values for $\underline{k}$.

Another objection of Brody's work is that in making the independent divisions of the growth curve, account was not taken of the relationship between one part of the curve and another part. Experimental data indicate that, in fact, correlations do exist between weights in the pre- and post-pubertal stages of the growth curve. These comments notwithstanding, Brody has a reasonable approach since the two functions at least represent the rate of gain not as an explicit function of time but of the conditions of the individual itself.

Monomolecular Autocatalytic Function

Robertson, in his 1923 book entitled "The Chemical Basis of Growth and Senescence" points out that the growth of organisms occurs in cycles. These cycles consist of a period of slow growth, followed by a period of relatively rapid growth and end in another period of slow growth. He suggested that the chemical process analogous to this type of growth was the monomolecular autocatalytic process. He suggested that the process by which an organism grows can be described by the following equation:

$$\frac{dW_x}{dx} = kW_x(W_\infty - W_x) \quad . \tag{2.7}$$

This equation indicates that the rate of gain is dependent on the growth already made and the growth yet to be made.

Integrating equation (2.7) with respect to time from t' to t, he obtained:

$$\int_{t'}^{t} \frac{dW_x}{W_x(W_\infty - W_x)} = k \int_{t'}^{t} dx$$

$$\frac{1}{W_\infty} \ell n \left(\frac{W_\infty - W_t}{W_t} \right) = \frac{1}{W_\infty} \ell n \left(\frac{W_\infty - W_{t'}}{W_{t'}} \right) - k(t-t')$$

$$\frac{W_\infty - W_t}{W_t} = \left(\frac{W_\infty - W_{t'}}{W_{t'}} \right) e^{W_\infty k(t-t')}$$

$$W_t = \frac{W_\infty}{1 + \left(\frac{W_\infty}{W_{t'}} - 1\right) e^{-W_\infty k(t-t')}} \quad . \tag{2.8}$$

The monomolecular autocatalytic function satisfies the properties of the sigmoid curve. It has lower and upper asymptotes at zero and $\underline{W_\infty}$, respectively, and has the weight at the point of inflection at $\underline{W_\infty/2}$, which means that it is a symmetrical curve. The weight at the inflection point is found by differentiating equation (2.7) with respect to time, setting it equal to zero and solving for the weight. The time at the inflection point (t*), found by substituting this result into equation (2.8) and solving, is:

$$t^* = \frac{1}{kW_\infty}\left[\ell n(W_\infty - W_o) - \ell n W_o\right], \quad \text{when } t' \text{ equals zero.} \tag{2.9}$$

Robertson suggested that, "... the magnitudes of these parameters may ultimately be found to afford, under given dietary conditions, a means of defining the several races quite as trustworthy as their external characteristics, while the behavior of the parameters in hybridization may be expected to throw an important light upon the mechanism of size-inheritance". A modification of Robertson's function was used by Hendricks et al. (1929) to study early growth (hatching to 15 weeks of age) of White Leghorn chickens. Criticism of the Robertson's function is that empirical data show the growth curve to be asymmetrical.

Robertson recognized that not only can the growth process be brought to a halt ($dW_x/ dx = 0$) when the organism has reached final weight ($W_x = W_\infty$) but also when the loss in weight is equal to the increase in weight. He couched this in chemical terms by noting that, "a chemical reaction may be brought to a stop in either of two ways, namely, by exhaustion of the ... material undergoing transformation ... or by ... the acceleration of the reverse reaction to the point of equality of its velocity with that of the forward reaction".

He described this extension by the following differential equation:

$$\frac{dW_x}{dx} = k_1W_x(W_\infty - W_x) - k_2W_x^2 \tag{2.10}$$

where k_1 is the rate constant of the forward reaction and k_2 is the rate constant of the reverse reaction.

Equation (2.10) may be rearranged as follows:

$$\frac{dW_x}{dx} = (k_1 + k_2)\, W_x \left(\frac{k_1}{k_1 + k_2}\, W_\infty - W_x \right)$$

and when integrated from t' to t, yields:

$$W_t = \frac{W_\infty}{\frac{1}{A} + \left(\frac{W_\infty}{W_{t'}} - \frac{1}{A} \right) e^{-k_1 W_\infty (t-t')}} \tag{2.11}$$

where $A = k_1 / (k_1 + k_2)$.

The above theory obviates a criticism of Robertson's original function, equation (2.8), namely that the curve is symmetrical since the weight at the point of inflection is $AW_\infty / 2$. However, a problem is introduced in that it is difficult to determine whether the cessation of growth is due to the organism having reached its final weight per se, or to the inhibitory effect of growth equaling the stimulatory effect.

Robertson generalized his monomolecular autocatalytic function by relaxing the restriction that the forward and reverse reactions be monomolecular. Thus, weight was raised to a power (m or n) which was not necessarily one. The rate of the forward reaction was defined to be:

$$\frac{dW_x}{dx} = k_1 W_x W_\infty^n \tag{2.12}$$

while the rate equation of the reverse reaction was:

$$\frac{dW_x}{dx} = -k_2 W_x^{m+1} \quad . \tag{2.13}$$

Thus, the net effect forward and reverse reactions or the actual rate of gain was given by:

$$\frac{dW_x}{dx} = k_1 W_x W_\infty^n - k_2 W_x^{m+1}$$

$$= k_2 W_x \left(\frac{k_1}{k_2} W_\infty^n - W_x^m \right) \quad . \tag{2.14}$$

The integrated form of the equation, evaluated at <u>t'</u> and <u>t</u> is:

$$W_t = \frac{W_\infty^n}{\frac{1}{A'} + \left(\frac{W_\infty^n}{W_{t'}^m} - \frac{1}{A'} \right) e^{-mA' W_\infty^n k_2 (t-t')}} \tag{2.15}$$

where $A' = k_1 / k_2$.

The maximum rate of gain is obtained when the weight is:

$$W_t = \left(A' \frac{W_\infty^n}{(m+1)} \right)^{1/m} \quad . \tag{2.16}$$

Note that when $k_1 = k_2 = k$ and $n = m = 1$, equation (2.16) reduces to the original monomolecular autocatalytic function, namely $\underline{W_\infty/2}$.

Generalized Monomolecular Autocatalytic Function

Pearl and Reed, in 1923, generalized Robertson's monomolecular autocatalytic function, equation (2.7) to a series function of time:

$$\frac{dW_x / dx}{W_x(W_\infty - W_x)} = k_1x + k_2x^2 + \ldots + k_nx^n \quad . \tag{2.17}$$

The objection to this method of generalization, as Brody points out, is that the values for the constants $(k_1, k_2, \ldots, k_n)$ may change when the value of n changes. Therefore, there are no unique estimates for these parameters and, for our purposes, their interpretations are not meaningful. Kavanagh and Richards (1934) mathematically relate the Pearl and Reed function with Robertson's autocatalytic growth curve by reducing them both to a form of the hyperbolic tangent function. They show that when the initial weight is zero, the hyperbolic tangent function becomes the logistic function.

Logistic Function

In 1838, Verhulst (Allee et al., 1949) developed an equation describing population growth and its relation to population density. He termed this S-shaped curve the logistic curve. The general properties of the logistic curve are: firstly, zero is the lower asymptote or limiting point, which is consistent with the growth phenomenon since negative values are impossible; secondly, there is an inflection point (when the rate of gain is a maximum); and thirdly, there is an upper asymptote, as the rate of gain tends towards zero, since the growth is limited.

The rate of gain equation from which the logistic function was derived is:

$$\frac{dW_x}{dx} = kW_x \left(\frac{W_\infty - W_x}{W_\infty}\right) \quad . \tag{2.18}$$

This differential equation indicates that the instantaneous rate of gain is a function of both growth already made and the potential for growth.

Rearranging equation (2.18) and then integrating, using partial fractions, from t' to t with respect to time, we obtain:

$$\frac{dW_x}{W_x \left(\frac{W_\infty - W_x}{W_\infty}\right)} = kdx$$

$$\int_{t'}^{t} \left[\frac{1}{W_x} + \frac{1}{W_\infty - W_x}\right] dW_x = k \int_{t'}^{t} dx$$

$$\ln \left(\frac{W_{t'}(W_\infty - W_t)}{W_t}\right) = \ln (W_\infty - W_{t'})\, e^{-k(t-t')}$$

$$W_t = \frac{W_\infty}{1 + \left(\frac{W_\infty - W_{t'}}{W_{t'}}\right) e^{-k(t-t')}} \quad . \tag{2.19}$$

Equation (2.19) relates the weight at a given time to a function of the initial and final weights, the growth rate constant and the time.

Solving for the weight at the inflection point, we obtain:

$$W_{t*} = \frac{W_\infty}{2} \quad , \tag{2.20}$$

where t^* is the time at the point of inflection. Thus, the weight at the point of maximum gain is one-half of the maximum weight. Substituting this result for W_{t^*} in equation (2.19) and solving for t^* we obtain, after some algebraic manipulations, the time at the inflection point to be:

$$(2.21) \qquad t^* = \frac{1}{k}\left[\ell n\,(W_\infty - W_{t'}) - \ell n W_{t'}\right] + t' \quad .$$

Note that when $(t-t') \to -\infty$, $t = t'$, $t = t^*$ and $(t-t') \to \infty$, equation (2.19) becomes zero, $W_{t'}$, $W_\infty/2$ and W_∞, respectively. Thus, the basic properties of the sigmoid curve, including the inflection point, is satisfied by the logistic function.

It would be unfair to say that the logistic function is beyond criticism with respect to its use in studying the growth of chickens. For example, the point of inflection is fixed at 50 percent of the maximum weight $(W_\infty/2)$. This restriction makes the curve symmetrical about the inflection point. Empirically the growth curve of chickens has been found to be asymmetrical. In addition, there is nothing unique about the fact that the logistic equation satisfies the general properties of growth curves. It would be wrong to designate the logistic function as *the law* of growth. Nevertheless, several investigators have applied the logistic function to their growth data.

Sang (1962) used the logistic function to analyze the mean growth of selected lines of Brown Leghorns. His purpose was to answer the question, "Do the lines differ because they have different intrinsic growth rates [k values], or because they have different genetically determined adult weights, or both?"

The function that he used to describe the body weight curve was: $W = A/(1 + e^{c-kt})$ which, although not in the same form, is comparable to equation (2.19). Of more interest than the absolute values of $\underline{k}$ were their relative values. He found no sizeable differences among the $\underline{k}$ values for the six lines of chickens. Although there were differences among the growth curves, his logistic slopes, $\Delta(W_\infty - W_t) / W_t / \Delta(\log t)$, were fairly constant among lines. This result indicated to him that the adult weight played an important role in determining the growth pattern. Sang found that, across lines, there were no relationships between the growth rate constant and the age at the point of inflection nor between age at sexual maturity and time at one-half of the final weight. Within a cross, however, the males had a higher growth rate constant than the females.

Krause et al. (1967), fitted the logistic function to juvenile body weights of Athens-Canadian randombred chickens from 20 to 140 days of age. They considered the entire growth pattern to be a "functional observation" and each individual's curve to be a unique entity. Their stochastic development used the three element vector of parameters as a multivariate observation. In their example they used the deterministic logistic function in the form: $W_t = \beta / (1 + \alpha e^{-\gamma t})$ where, in terms of equation (2.19): $\beta = W_\infty$, $\alpha = [(W_\infty/W_{t'}) - 1]$ and $\gamma = k$. The estimate of $\underline{k}$ was calculated to be 0.1635, based on weights of six full brothers taken at four day intervals. Although the assumption of independent stochastic parameters was violated, they suggested that the stochastic representation may be useful in studies of the inheritance of growth patterns.

The study was continued in a thesis project by Mendel (1965) to determine the inheritance of the growth curve parameters during selection. He suggested that the set of stochastic parameters be estimated by a multivariate least squares procedure. After the parameters were estimated on individual chickens, they were subjected to a hierarchical genetic analysis of variance. Of particular interest were the analyses, on male and female progeny, of the stochastic parameter γ, the intrinsic growth rate constant. Table (2.1) shows the percent of variation in γ due to sires, dams and progeny in males and females.

Table 2.1. Hierarchical Analyses of Variance on Male and Female Progeny for the Intrinsic Growth Rate Parameter, γ[a]

		Percent of Variation	
Source	d.f.	Males	Females
Sires (S)	13	11.09	3.20
Dams (D)/S	36	14.63	18.97
Progeny/D/S	110	74.27	77.82

[a] Taken from Mendel (1965)

These results indicated considerable non-additive or maternal effects in the female progeny and to a somewhat less extent in the male progeny. In both sexes, differences among full sib progeny accounted for the majority of the total phenotypic variance.

In work with mice, Carmon (1965) did statistical analyses on functions of the growth parameters of the logistic curve. For the growth parameter (e^{-k}) estimated for each individual, he estimated the percentage of the total variance accounted for by differences among sires, dams and full sib progeny. He found that the random error accounted for 93.6 percent of the total variation while the dam component accounted for 5.6 percent. The differences among sires contributed a negligible amount to the total variance of the population with regard to the growth parameter.

The sire and dam components had the following genetic interpretation (ignoring epistasis):

$$\sigma_S^2 = \frac{1}{4}\sigma_a^2$$

$$\sigma_D^2 = \frac{1}{4}\sigma_a^2 + \frac{1}{4}\sigma_d^2 + \sigma_m^2$$

where: σ_a^2 = additive genetic variance

σ_d^2 = dominance variance

σ_m^2 = common environmental variance, e.g. maternal effects.

Therefore, the difference between the sire and dam components of variance $(\sigma_D^2 - \sigma_S^2)$ estimated the amount of dominance variance and maternal effects (see Falconer, 1960). The results indicated considerable dominance and/or maternal effects for the growth parameter $(\underline{e}^{-k})$ in mice.

Generalized Logistic Function

In 1961, Nelder described the fitting of a four parameter function defined by the differential equation:

$$\frac{dW_x}{dx} = kW_x \{1 - (\frac{W_t}{W_\infty})^{1/\theta}\} \quad . \tag{2.22}$$

This function is a generalization of the logistic function. Note that when $\theta = 1$, equation (2.22) is equivalent to the differential equation for the logistic function, equation (2.18).

When integrating equation (2.22) from t' to t, with respect to time, for values of θ greater than zero, he obtained:

$$(2.23) \qquad W_t = \frac{W_\infty}{\{1 + [(\frac{W_\infty}{W_{t'}})^{\frac{1}{\theta}} - 1]\, e^{\frac{-k(t-t')}{\theta}}\}^{\theta}} \, .$$

Equation (2.23) expresses weight at a given time in terms of the initial and final weights, the growth rate constant, time and θ. Nelder et al. (1960) interpreted θ to be an external factor affecting growth in a regular environment, for example, soil or nutrient supply.

The restriction that Nelder placed on θ, namely that it be greater than zero, was relaxed to include both positive and negative values. Therefore, Nelder (1962) reparameterized equation (2.22) to:

$$(2.24) \qquad \frac{dW_x}{dx} = kW_x\{1 - (\frac{W_t}{W_\infty})^u\}$$

by letting $u = 1/\theta$. Upon integration, from t' to t, equation (2.24) becomes:

$$(2.25) \qquad W_t = \frac{W_\infty}{\{1 + [(\frac{W_\infty}{W_{t'}})^u - 1]\, e^{-uk(t-t')}\}^{1/u}} \, .$$

The interpretation of u must be similar to that of θ, however, its relation to the organism is difficult to specify.

Nelder's generalized logistic still maintains the necessary properties for a growth curve. Namely, when $(t-t') \rightarrow -\infty$, $t = t'$, and $(t-t') \rightarrow \infty$, equation (2.25) becomes zero, $W_{t'}$, and W_∞, respectively. An important consequence of this generalization are the resulting values for the coordinates of the point of inflection. The weight at the inflection point, using the derivative of equation (2.24), is:

$$W_{t*} = \frac{W_\infty}{(u + 1)^{1/u}} \quad , \tag{2.26}$$

and the time at the inflection point is:

$$t* = \left[\frac{\ell n(W_\infty^u - W_{t'}^u) - \ell n(W_{t'}^u) - \ell n(u)}{uk}\right] + t' \quad . \tag{2.27}$$

An advantage of Nelder's generalized logistic function is that when $u \neq 1$ the curve is asymmetrical. Since the point of inflection is not a fixed percentage of the final weight this growth function is more flexible than the logistic function presented in the previous section.

Gompertz Function

The Gompertz function, named after Benjamin Gompertz who published it in 1825 (see Winsor, 1932), possesses similar properties as the monomolecular autocatalytic and the logistic functions. A comparison between the logistic and Gompertz function is presented by Verhagen (1960). In the Gompertz function, rate of gain is a function of the weight of the individual and the gain to be made . Thus the differential equation, in terms of natural logarithms, is:

(2.28) $$\frac{dW_x}{dx} = kW_x\ (\ell nW_\infty - \ell nW_x) \quad .$$

Integrating equation (2.28) with respect to time we obtain:

$$\int_{t'}^{t} \frac{dW_x}{W_x(\ell nW_\infty - \ell nW_t)} = k\int_{t'}^{t} dx$$

(2.29) $$W_t = W_\infty\ e^{-(\ell nW_\infty - \ell nW_{t'})e^{-k(t-t')}} \quad .$$

Equation (2.29) defines the weight at time $\underline{x}$ as a function of the logarithms of the initial and final weights, the growth rate constant and time.

From equation (2.28), the weight at the point of inflection is:

(2.30) $$W_{t*} = \frac{W_\infty}{e} \sim \frac{W_\infty}{2.7183} \quad .$$

The weight at maximum gain is about 37 percent of the upper asymptotic weight. Substituting this result for $\underline{W_{t*}}$ in equation (2.29) and solving for $\underline{t*}$, the time at the inflection point is obtained to be:

(2.31) $$t* = \frac{1}{k}\ \ell n[\ell nW_\infty - \ell nW_{t'}] + t' \quad .$$

In the Gompertz function as in the logistic function and the monomolecular autocatalytic function, when $(t-t') \rightarrow -\infty$, $t = t'$, and $(t-t') \rightarrow \infty$ equation (2.29) becomes, respectively, zero, $W_{t'}$ and W_∞. Where the Gompertz function differs from the previous two functions, however, is in its lack of symmetry. As pointed out, the inflection point occurs at (W_∞/e) or about 37 percent of the final weight.

Laird et al. (1965) derived a form of the Gompertz function based on the observation by Wright (1926) that the instantaneous relative growth rate decays approximately exponentially with age. The instantaneous relative growth rate (which they call the specific growth rate) $\gamma = (dW_x/dx)/W_x$ is equivalent to $k(\ell nW_\infty - \ell nW_x)$ in the notation presented here. The rate at which the instantaneous relative growth rate decreases with time, $d\gamma/dx$, is $-k(1/W_x)(dW_x/dt) = -k\gamma$. The growth rate $(\underline{k})$, equivalent to their $\underline{\alpha}$, is a biological constant for the process of growth described by a single Gompertz curve. Whereas values for $\underline{W_t}$ and $\underline{W_t}$, depend on the point taken as the initial time, $\underline{k}$ should remain unchanged.

In 1966, Laird published estimates for $\underline{k}$, based on data collected by other workers, using a compound function in terms of weight accumulated by the Gompertz process and by a linear growth process. Estimated values for $\underline{k}$, based on post-hatching data for White Leghorn males and females were 0.0256 ± .0007 and 0.0341 ± .0005, respectively. The fact that the value for $\underline{k}$ is larger for females, indicated to Laird, "... a general tendency for the female of the species to pass through her growth period faster and to mature earlier than the male".

Bertalanffy Function

Bertalanffy (1957 and 1960) took a somewhat more fundamental approach in his study of growth using the concept of "organismic biology". He mentions in 1957 that, "... growth of even a simple organism is a tremendously complex phenomenon from the biochemical, physiological, cytological and morphological viewpoints". Although he felt that his organismic approach would give some insight into the relationships between growth and metabolism, he did not fail to recognize that absolute body size was a very important factor determining the rate of "the system".

It was known for a long time, in fact, that in mammals a relationship existed between metabolic rate and body weight through surface area. As Bertalanffy explains the "surface rule", the surfaces of two bodies of similar shape are related by the 2/3 power of their linear dimension, weight. Then $S = cW^{2/3}$, where S is the surface area, c the proportionality constant and W the body weight. Since metabolic rate is directly proportional to body surface, the relation between metabolic rate and body size can be expressed by the allometric equation $M = bW^{\alpha}$, where M is the metabolic rate per unit time, b the proportionality constant and α the allometric constant.

The allometric constant may take on values from 2/3 to 1 depending on the different types of relationships between metabolic rate and body size. Briefly, the three metabolic types are where:

1) Metabolic rate is proportional to a surface or the 2/3 power of weight ($\alpha = 2/3$). Fish and mammals are representative of this type.
2) Metabolic rate is proportional not to surface area but to weight itself ($\alpha = 1$). Insect larvae belong to this type.
3) Metabolic rate is intermediate between proportionality to body weight and to survace area ($2/3 < \alpha < 1$). Flatworms have this metabolic type.

As there are different metabolic types, there are also different growth types distinguished by their growth curves. Animal growth can be considered a correlated response to the processes of anabolism and catabolism of the building materials of the body. The change in body weight, dW_x/dx, is given by the difference between the processes of synthesis and destruction and expressed in the general formula:

$$\frac{dW_x}{dx} = aW_x^m - cW_x^n \tag{2.32}$$

where $\underline{a}$ and $\underline{c}$ are proportionality constants of anabolism and catabolism respectively and $\underline{m}$ and $\underline{n}$ are exponents indicating that the rate of change is proportional to a power of the body weight $\underline{W_x}$. Based on previous findings that the rate of catabolism is directly proportional to weight, and perhaps because an exact solution exists, Bertalanffy set $n = 1$. Rearranging and integrating equation (2.32) with respect to time,

$$\frac{dW_x}{dx} = cW_x(1 - \frac{a}{c} W_x^{m-1}) \tag{2.33}$$

$$\int_{t'}^{t} \frac{dW_x}{W_x(1 - \frac{a}{c} W_x^{m-1})} = - c \int_{t'}^{t} dx = - c(t-t')$$

$$W_t = \{\frac{a}{c} - (\frac{a}{c} - W_{t'}^{(1-m)})e^{-c(1-m)(t-t')}\}^{\frac{1}{1-m}} \tag{2.34}$$

where $\underline{W_{t'}}$ is the weight at initial time, $\underline{t'}$. A value for $\underline{m}$ is inserted based on the dependence of resting metabolism on body weight.

When $(t-t') \rightarrow \infty$, the upper asymptote, W_∞, equals $(\frac{a}{c})^{\frac{1}{1-m}}$.

In chickens, the value for $\underline{m}$ has been found to be 0.744 (Sturkie, 1965, p. 246) since the relation between metabolic rate in (kcal)/(24 hr) and body weight in kilograms was best expressed by:

$$\log M = \log 74.3 + 0.744 \log W$$

$$\text{or} \quad M = 74.3W^{0.744} .$$

Leighton et al. (1966) studied the relationship between surface area and body weight in 114 Athens-Canadian randombred chickens of both sexes. They weighed the birds, skinned them and measured the area of the skin. By the linear regression technique they found that the log of surface area was related to the log of body weight as:

$$\log S = \log 4.9876 + 0.75417 \log W \text{ for males,}$$

$$\log S = \log 5.6774 + 0.73264 \log W \text{ for females and,}$$

$$\log S = \log 5.2860 + 0.74461 \log W \text{ for the sexes combined.}$$

Since metabolic rate is directly proportional to surface area this appears to verify the relationship between metabolic rate and body weight, as presented by Sturkie.

Thus, it appears that chickens follow the third metabolic type, where the metabolic rate is intermediate between 2/3 and 1. Inserting a value for $\underline{m}$ of 0.744 the curve of weight would be sigmoid with the weight at the point of inflection $(\underline{W_{t*}})$ equal to $1.0745\ (a/c)^4$.

Richards (1959) objected to some of the assumptions contained in the derivation of Bertalanffy's growth function. For example, he points out that values of $\underline{m}$ greater than one are rejected, not because they do not occur biologically, but because with such values of $\underline{m}$, $\underline{a}$ and $\underline{c}$ would be negative. This would invalidate their interpretation as proportionality constants of anabolism and catabolism. Yet, he says, empirically Bertalanffy's general function requires m to take on values greater than one for wide application. For example, when $m = 2$, Bertalanffy's function is reduced to a function in the form of the logistic. When $m = 1$, the Bertalanffy formula becomes a Gompertz type curve, and a and c become equal and infinitely great. As m varies from zero through one and two a family of curves is produced. Unfortunately, Richards offers no method of estimating m other than by empirical means.

It is the purpose of this research to determine a mathematical growth function that "best" describes or fits the body weight curve of four specific populations of chickens from hatching to 45 weeks of age. Included among the parameters of the growth function is an intrinsic growth rate constant (k), distinct from the average change in weight or rate of gain. The intrinsic growth rate constant was studied since it expresses the rate of gain as a function of the weight at a given time and the gain to be made. From among the growth formulae expressing gain as a function of the intrinsic growth rate constant, the logistic function was chosen to be studied. Despite the objections to the logistic functions, namely that it is symmetric and has a fixed point of inflection, it has several advantages. Growth rate based on the logistic function has been studied previously and comparisons among results can be made. Procedures for estimating the intrinsic growth rate constant have been theorized for the logistic function and an experimental test of these procedures can be performed. Procedures for estimating the intrinsic growth rate constant were important since it was also the purpose of this thesis to test the hypothesis that the intrinsic growth rate constant, based on the logistic distribution, is an inherited characteristic. To do this, individual estimates of the intrinsic growth rate constant were essential.

MATERIALS AND METHODS

Description of the Populations and Environment

This phase of the experiment utilized the data collected on the populations described in Chapter I. Only those progeny which survived to 45 weeks of age were included in the populations.

Description of the Traits

The primary characteristic measured was individual weekly body weight from hatching to 45 weeks of age. The method of taking the weights is outlined in Chapter I. The secondary traits studied were the initial and maximum weights, age at point of inflection and the intrinsic growth rate constant. These traits are important for several reasons. Firstly, they are parameters in the growth functions (see for example equations (2.19) and (2.21)) and must be estimated. Secondly, their relation to one another determines the shape of the growth curve. Thus, in any attempt to change the shape of the growth curve, knowledge about any change in these parameters is essential.

Description of Statistical Procedures

Estimation of Parameters of the Logistic Function

The function used to describe the growth pattern of chickens was the logistic function. The logistic function was chosen for several reasons. It has a sigmoid shape and resembles the entire growth curve.

It is a function of the intrinsic growth rate constant which relates rate of gain to the weight at a given time and the gain yet to be made. Several theoretical parameter estimation procedures have been proposed and a discussion of these methods would be useful.

Nair (1954) suggested several methods for fitting the growth curve based on the logistic function. These methods estimated the parameters by calculating the linear regression of the transformed variable, $Z_t = (W_{t+1} - W_t)/W_t$, on W_t. This technique was considered unsuitable since it was pointed out by Anderson (1968) that when a nonlinear function is transformed into a linear relationship, estimates of the parameters using the linear model could be different than estimates from the nonlinear model. A point estimation procedure was also presented by Nair (1954) using only the values at the two ends and in the middle of the growth curve. This procedure was not considered useful since the standard error of the parameter could not be obtained.

One method that was used to fit the data and obtain estimates of the parameters in the logistic function (equation 2.19) was the nonlinear regression procedure outlined by D. W. Marquardt (see Draper and Smith, 1966 pages 272-3). A computer program (IBM SHARE No. 3094) modified at Purdue University was used for the computations.

Another parameter estimation procedure, maximum likelihood estimation, using order statistics was theorized by Gupta and Gnanadesikan (1966). They estimated the location $(\underline{\mu})$ and scale $(\underline{\sigma})$ parameters of the logistic function:

$$(2.35) \qquad W = \frac{1}{1 + \exp[-a(x - \mu)/\sigma]} \quad .$$

Through transformation of the data, namely dividing all weights by the maximum weight reached during the 45 weeks, it is possible to relate their parameters, $\underline{\mu}$ and $\underline{\sigma}$, to the ones presented for the logistic function previously. Specifically, it can be shown that the intrinsic growth rate constant $(\underline{k})$ is equivalent to a/σ, where $a = \pi/\sqrt{3}$ and that $\underline{\mu}$ is the age at the point of inflection, $\underline{t}^*$. Using the case when both $\underline{\mu}$ and $\underline{\sigma}$ were to be estimated (case C of Gupta and Gnanadesikan, 1966), order statistics was used to obtain estimates of the intrinsic growth rate constant and age at the inflection point from weekly mean body weights of each population. The same procedure was used to estimate both parameters from each individual's data.

Heritability of the Logistic Parameters

Heritability in the narrow sense (h^2) is defined as the proportion of total variance of a random variable which is attributed to the variance among breeding values. Thus, heritability is the ratio of the additive genetic variance to the phenotypic variance (σ_A^2/σ_P^2) and indicates the degree to which the phenotype of a trait corresponds to the genotype (Falconer, 1960). Heritability is an important statistic in predicting response to selection for improving the genotype. Therefore, in any selection program to change the genotypic mean, of say, the intrinsic growth rate constant in the population (and thereby change the shape of the growth curve), an estimate of the heritability of the growth rate is essential.

Heritability estimates based on paternal and maternal half sib and full sib correlations (see e.g. Falconer, 1960 and King and Henderson, 1954) were calculated from individual estimates of the intrinsic growth rate constant and the age at the inflection point. A computer program for an unequal subclass number nested analysis of variance was used to do the calculations (Bogyo, 1965 as modified by Gall 1967, personal communication).

The form of the nested analysis of variance of the variable $\underline{k}$ is presented in Table 2.2. The assumed model is:

$$k_{ijm} = \mu + S_i + D_{ij} + \epsilon_{ijm}$$

where:

k_{ijm} = the observed growth rate constant of the mth individual from the jth dam mated to the ith sire

μ = the theoretical mean

S_i = the differential effect of the ith sire, $i = 1,\ldots,s$

D_{ij} = the differential effect of the jth dam mated to the ith sire, $j = 1,\ldots, d_i$ and

ϵ_{ijm} = the random error, $m = 1,\ldots, n_{ij}$ progeny/dam/sire.

Furthermore:

$\sum_j n_{ij} = n_{i.}$ = the number of progeny/sire,

$\sum\sum_{ij} n_{ij} = N$ = total number of progeny.

The following assumptions are necessary:

1) $S_i \sim NID(0,\sigma_S^2)$, $D_{ij} \sim NID(0,\sigma_D^2)$, $\epsilon_{ijm} \sim NID(0,\sigma^2)$.

2) All effects are mutually uncorrelated.

Table 2.2. Form of the Nested Analysis of Variance

Source	d.f.	EMS*
Sires (S)	s-1	$\sigma^2 + k_2\sigma_D^2 + k_3\sigma_S^2$
Dams (D)/S	$\sum_i (d_i - 1)$	$\sigma^2 + k_1\sigma_D^2$
Progeny/D/S	$\sum\sum_{ij} (n_{ij} - 1)$	σ^2
Total	N - 1	

*Coefficients of variance components:

$$k_1 = \frac{1}{\sum_i (d_i - 1)} \left[N - \frac{\sum\sum_{ij} n_{ij}^2}{N}\right]$$

$$k_2 = \frac{1}{s-1} \left[\sum_i \left(\frac{\sum_j n_{ij}^2}{n_{i\cdot}}\right) - \frac{\sum\sum_{ij} n_{ij}^2}{N}\right]$$

$$k_3 = \frac{1}{s-1} \left[N - \frac{\sum_i n_{i\cdot}^2}{N}\right]$$

3) There are no interactions between sires and dams. This assumption is required so that the dam component of variance estimates one-fourth of the additive genetic variance.

Therefore, heritability estimates were calculated as follows:

$$h_S^2 = \frac{4\sigma_S^2}{\sigma_S^2 + \sigma_D^2 + \sigma^2},$$ when based on paternal half sib correlations (sire component),

$$h_D^2 = \frac{4\sigma_D^2}{\sigma_S^2 + \sigma_D^2 + \sigma^2},$$ when based on maternal half sib correlations (dam component) and

$$h_{S+D}^2 = \frac{2(\sigma_S^2 + \sigma_D^2)}{\sigma_S^2 + \sigma_D^2 + \sigma^2},$$ when based on full sib correlations.

Standard errors for the heritability estimates were calculated using the procedure suggested by Osborne and Paterson (1952) and, as applied in the unequal number case, by Dickerson (1963).

Genetic Correlations Among Logistic Parameters

Often when selection is applied to a trait, for example the intrinsic growth rate constant (k), there is an accompanying change in other related traits, for example the age at the point of inflection. The degree to which a related trait will change is a function of the genetic correlation between it and the trait to which selection is applied. The genetic correlation is defined as the correlation between the breeding values of two traits (Falconer, 1960).

Genetic correlation estimates between the parameters of the logistic function, equation (2.35), the intrinsic growth rate constant and age at the inflection point, were calculated from sire components, using the program of Bogyo (1965), based on the unequal subclass procedures of Grossman and Gall (1968). Therefore, the genetic correlation was estimated by:

$$r_G = \frac{\sigma_{S_1S_2}}{\sigma_{S_1} \cdot \sigma_{S_2}}$$

where: $\sigma_{S_1S_2}$ is the sire component of covariance between traits 1 and 2,

$\sigma^2_{S_1}$ is the sire component of variance for trait 1 and

$\sigma^2_{S_2}$ is the sire component of variance for trait 2.

Standard errors for the genetic correlation coefficients were calculated using the method suggested by Robertson (1959) when the heritabilities of the two variables are unequal.

RESULTS AND DISCUSSION

Parameter Estimates of the Logistic Function Based on Mean Weights

Based on the means of the observed weekly weights for the four populations, estimates of the parameters of the logistic function were obtained using the methods of nonlinear regression, equation (2.19), and order statistics, equation (2.35). By using both estimation procedures, comparisons can be made between the estimates of the parameters by each method. Estimates of the parameters will be presented first for the method of order statistics and then for the nonlinear regression procedure.

Parameter Estimates Based on the Method of Order Statistics

The method of order statistics (based on maximum likelihood estimation) requires constraints on the theoretical values such that the lower asymptote is zero and the upper asymptote is fixed at 1.00. Thus, the mean weights were transformed and expressed as a proportion of the maximum mean weight. The transformed and predicted mean weights, as well as differences between them are presented in Tables C1-C4 in Appendix C. The plots of the transformed and theoretical curves are presented in Figures 2.1-2.4, graphed as a percentage of the maximum weight.

Estimates of the intrinsic growth rate constant ($\underline{k}$) were obtained by first estimating $\underline{\sigma}$ and then equating $\underline{k}$ to a/σ where

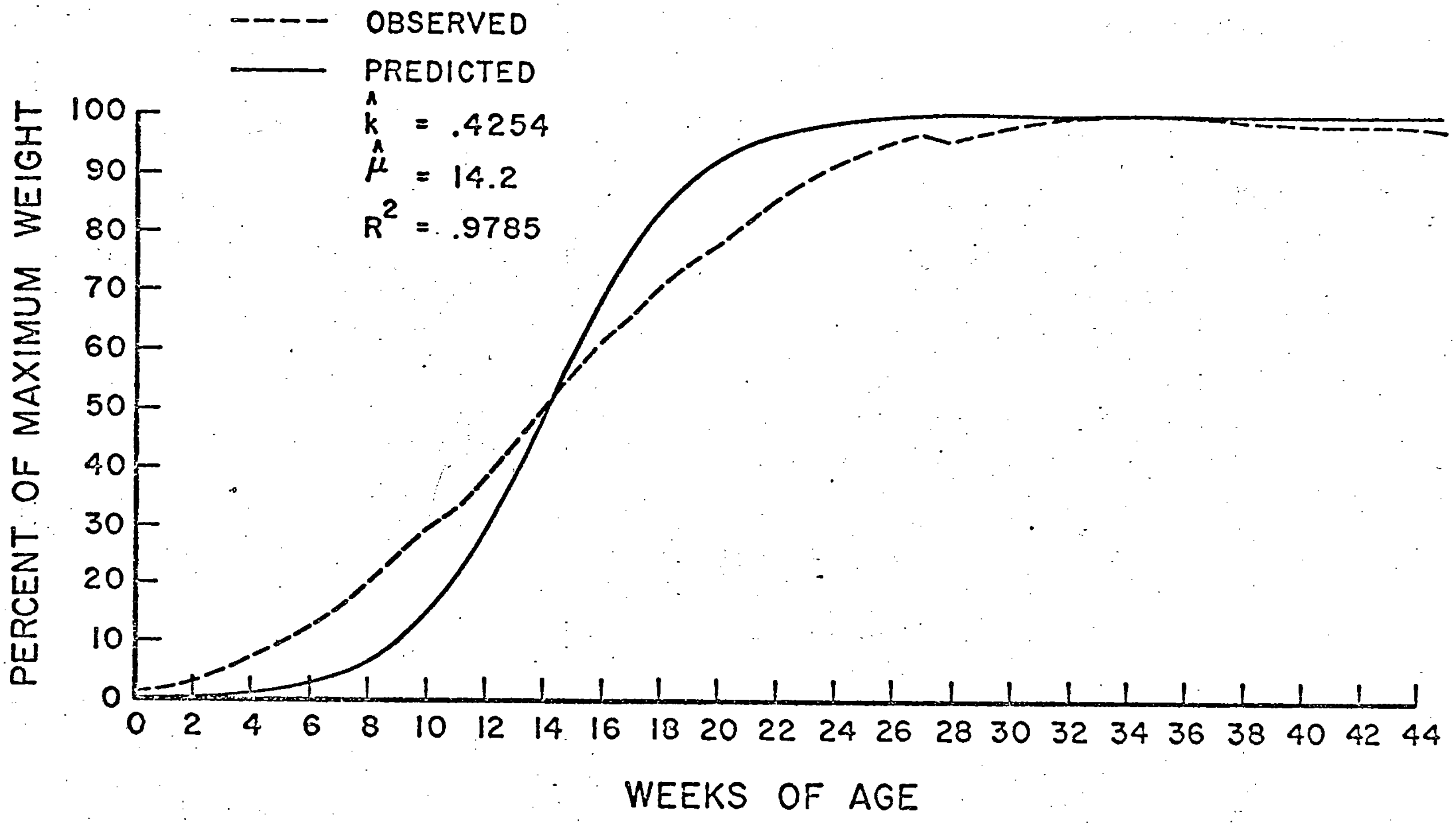


Figure 2.1. The Logistic Curve Fit to Mean Weights of Rhode Island Red Males by Order Statistics

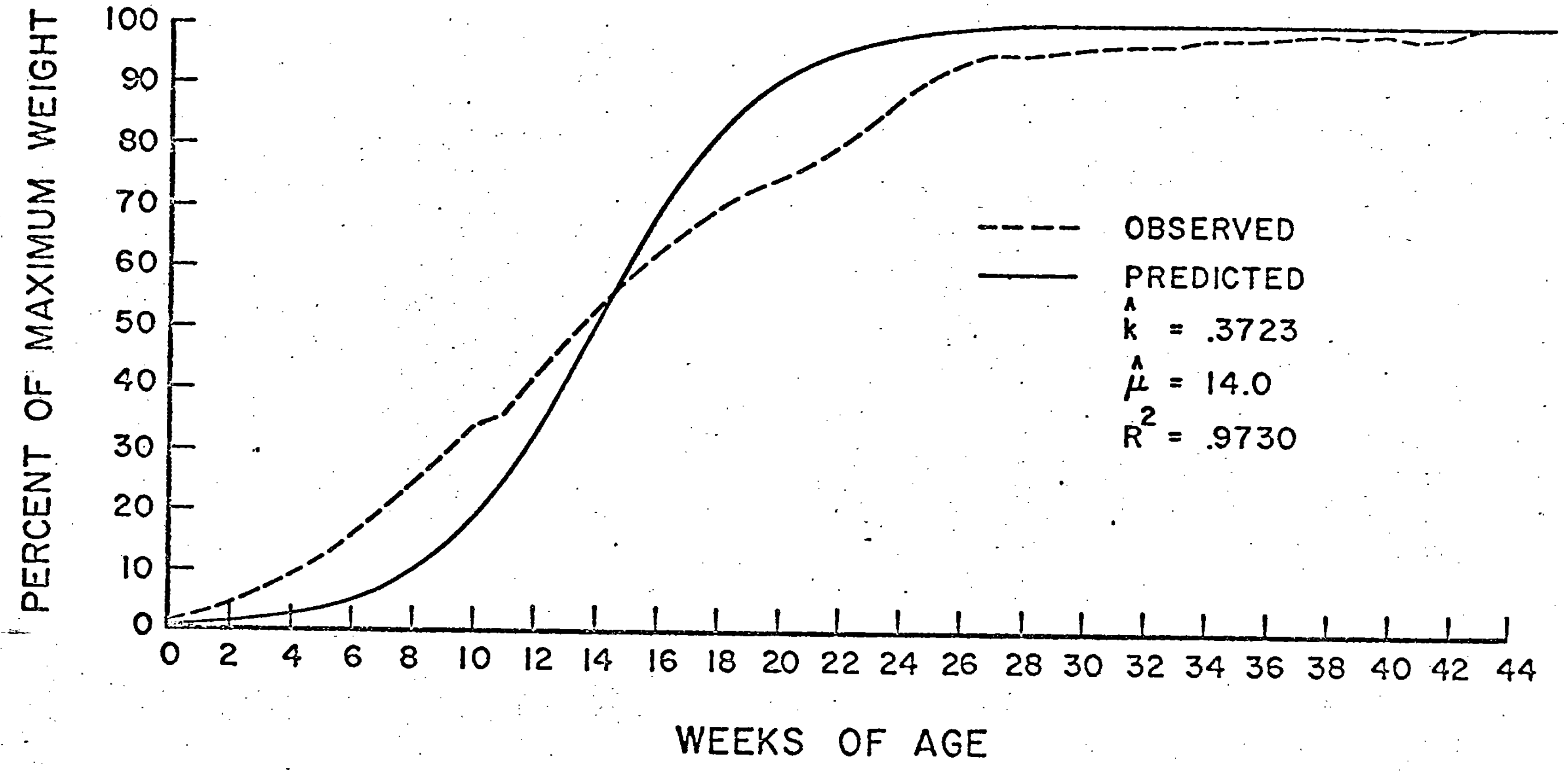


Figure 2.2. The Logistic Curve Fit to Mean Weights of Rhode Island Red Females by Order Statistics

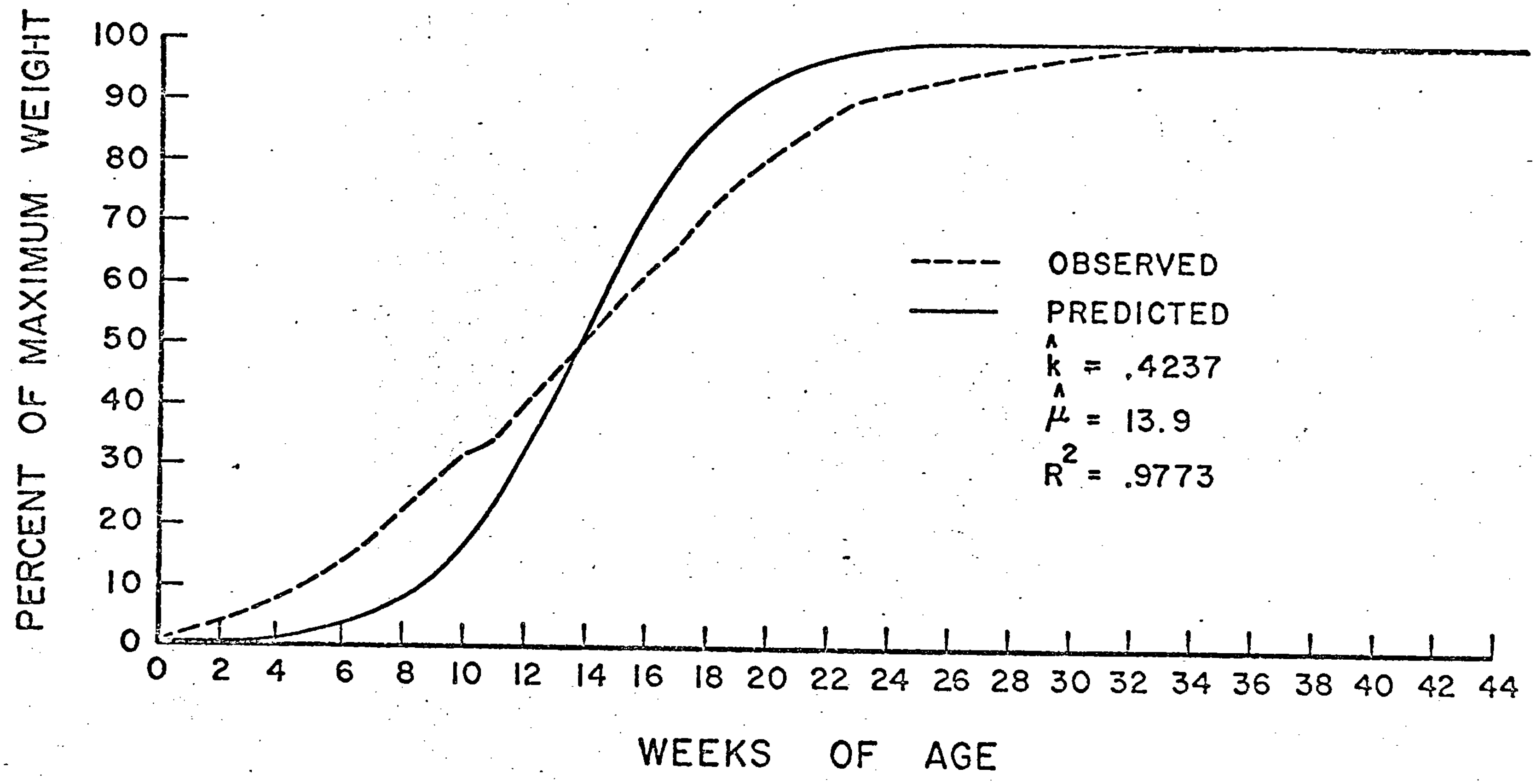


Figure 2.3. The Logistic Curve Fit to Mean Weights of White Leghorn Males by Order Statistics

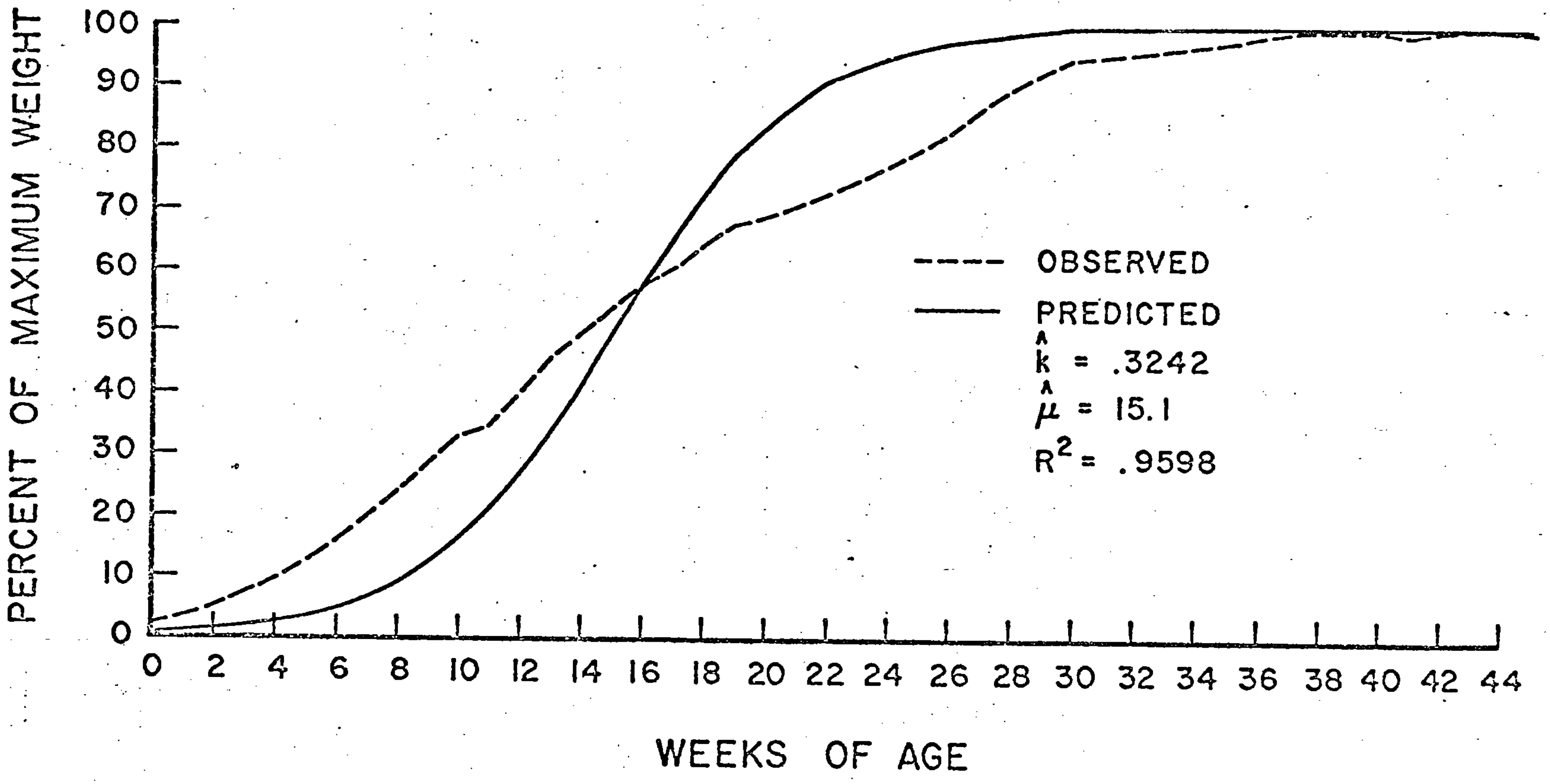


Figure 2.4. The Logistic Curve Fit to Mean Weights of White Leghorn Females by Order Statistics

$a = \pi / \sqrt{3}$. Table 2.3 presents the estimates of k values based on the weekly mean weights of each population.

Table 2.3. Estimated Values for Intrinsic Growth Rate Constant (k) by Order Statistics for Each Population

	Line		
Sex	RIR	WL	Average
Male	0.4254 ± .0064	0.4237 ± .0078	0.4246
Female	0.3723 ± .0065	0.3242 ± .0066	0.3482
Average	0.3988	0.3740	

The difference between the sexes (0.0764) was larger than the difference between the lines (0.0248) with respect to the average intrinsic growth rate constant. The males had a larger growth rate constant than the females of the same line; the estimates being 0.4254 vs. 0.3723 for the RIR line and 0.4237 vs. 0.3242 for the WL line. In comparing lines, the RIR line had a larger value for the rate constant than the WL line within a sex; the values being 0.4254 vs. 0.4237 for the males and 0.3723 vs. 0.3242 for the females.

As the theory dictated, the predicted curves were symmetrical about the mean (μ) or the age at the inflection point. The estimated values for the age at the point of inflection are presented in Table 2.4.

Table 2.4. Estimated Values for Age at the Point of Inflection ($\underline{\mu}$) by Order Statistics for Each Population

	Line	
Sex	RIR	WL
Male	14.2 ± .13	13.9 ± .16
Female	14.0 ± .18	15.1 ± .23

In the case of the males, the estimated age at the inflection point coincided with the point at which the predicted curve crossed the observed values (see Figures 2.1 and 2.3). In the females, however, the estimated value was smaller than that shown on the graph, namely 14.0 vs. 14.5 and 15.1 vs. 16.0 for the RIR and WL lines, respectively (see Figures 2.2 and 2.4). This information and the fact that the squared correlation coefficients between the observed and predicted values were larger for the males than for the females (0.9785 vs. 0.9730 in RIR line and 0.9773 vs. 0.9598 in WL line) indicates that the logistic function described the growth of the male populations better (in the sense of R^2) than the female populations when the parameters were estimated by order statistics.

Parameter Estimates Based on the Method of Nonlinear Regression

Nonlinear Regression Constraining Initial and Maximum Mean Weights.

To compare the nonlinear regression procedure with that derived by Gupta and Gnanadesikan (1966), using order statistics, only those mean weights up to the observed maximum were used. In addition, constraints were applied such that the predicted regression line was forced to go through both the observed initial and maximum mean weights. The maximum mean weight up to 45 weeks of age occurred at 34 and 37 weeks of age in the RIR and WL males and at 45 and 43 for the RIR and WL females, respectively. The observed and predicted weights, as well as the differences between them are presented in Tables C1 - C4. Figures 2.5 - 2.8 present graphs of the observed and predicted values for each population.

Estimates of the intrinsic growth rate constant (k) using the method of nonlinear regression are presented in Table 2.5.

Table 2.5. Estimated Values for the Intrinsic Growth Rate Constant (k) by Nonlinear Regression for Each Population

	Line		
Sex	RIR	WL	Average
Male	0.3038 ± .0039	0.2834 ± .0031	0.2936
Female	0.2826 ± .0047	0.2425 ± .0049	0.2626
Average	0.2934	0.2630	

The difference between the sexes (0.0310) was about the same as the difference between the lines (0.0304) with respect to the average intrinsic growth rate constant. The males had a larger growth rate constant than the females of the same line; the values being 0.3038 vs. 0.2826 for the RIR line and 0.2834 vs. 0.2425 for the WL line. When comparing lines, the RIR line had a larger value of k than the WL line for each sex; the estimates being 0.3038 vs. 0.2834 for the

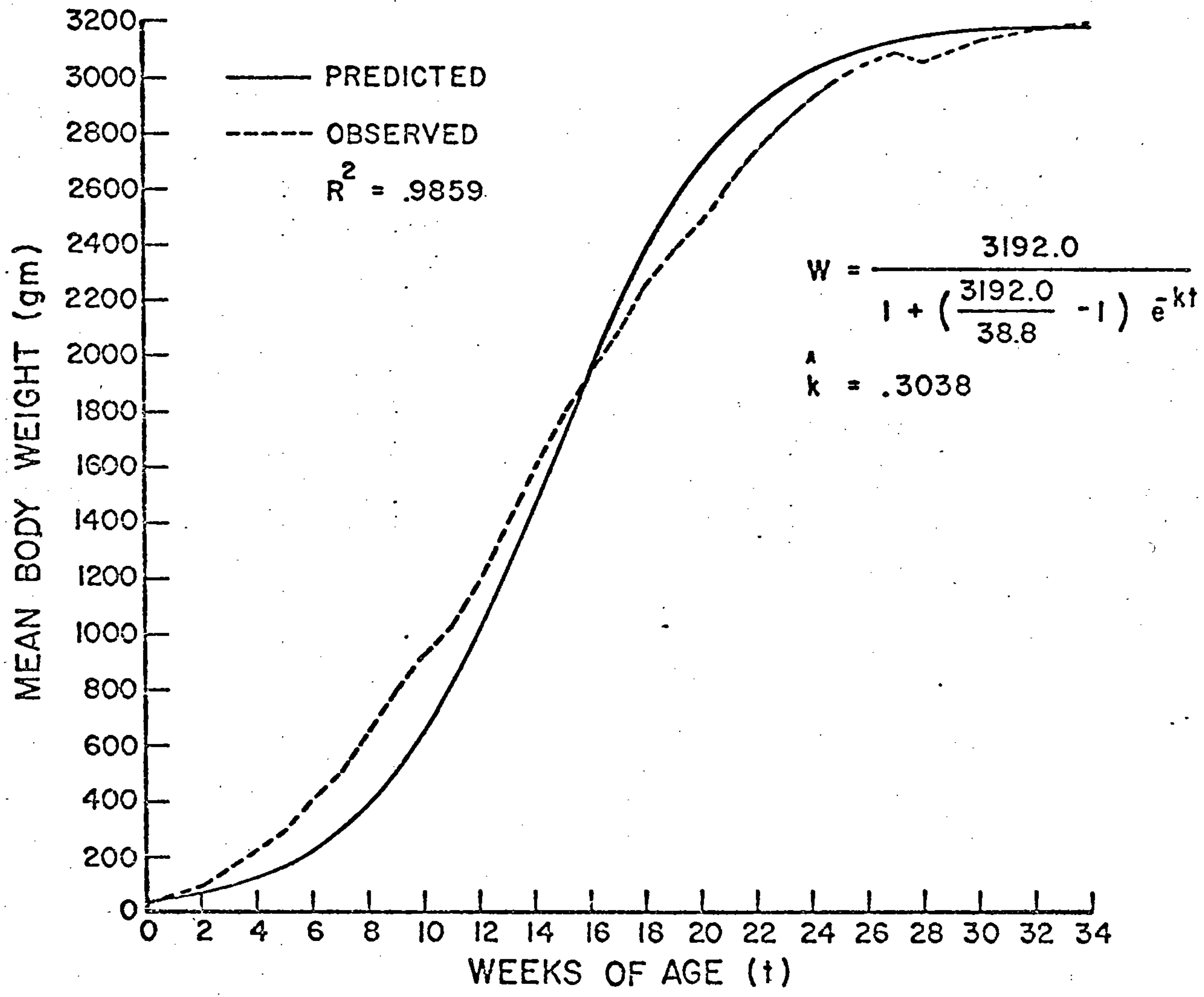


Figure 2.5. The Logistic Curve Fit to Maximum Mean Weights of Rhode Island Red Males by Nonlinear Regression

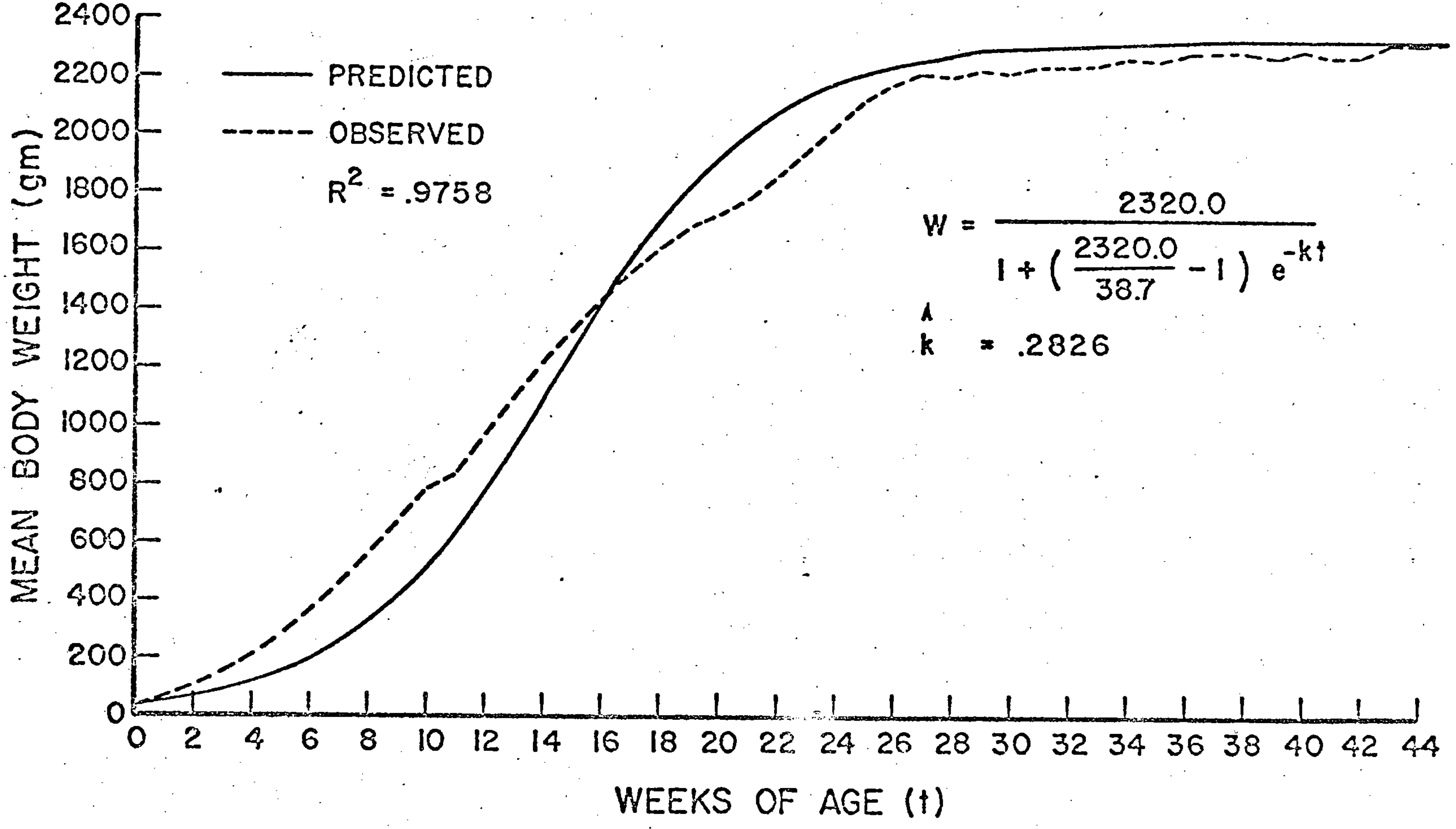


Figure 2.6. The Logistic Curve Fit to Maximum Mean Weights of Rhode Island Red Females by Nonlinear Regression

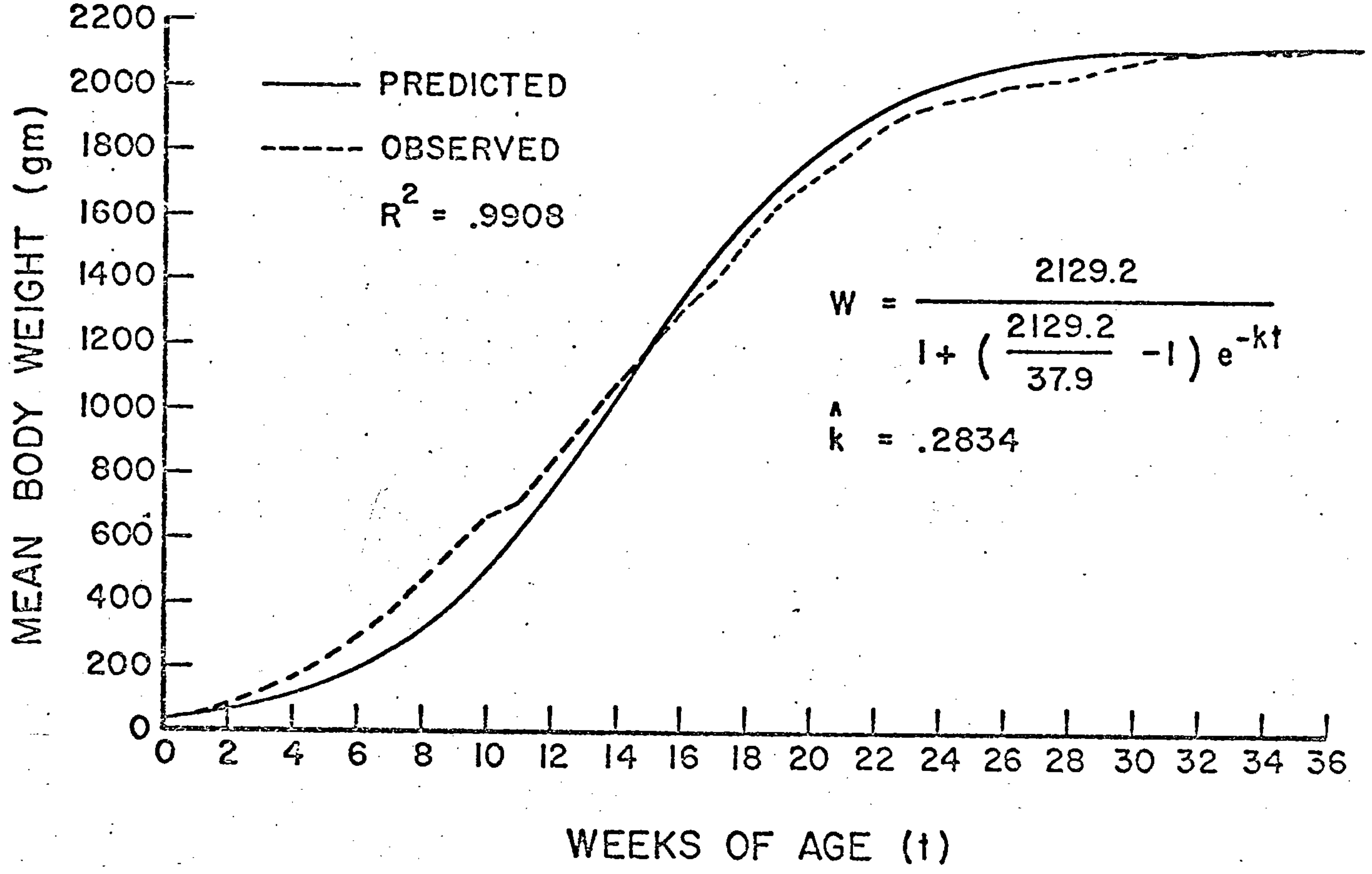


Figure 2.7. The Logistic Curve Fit to Maximum Mean Weights of White Leghorn Males by Nonlinear Regression

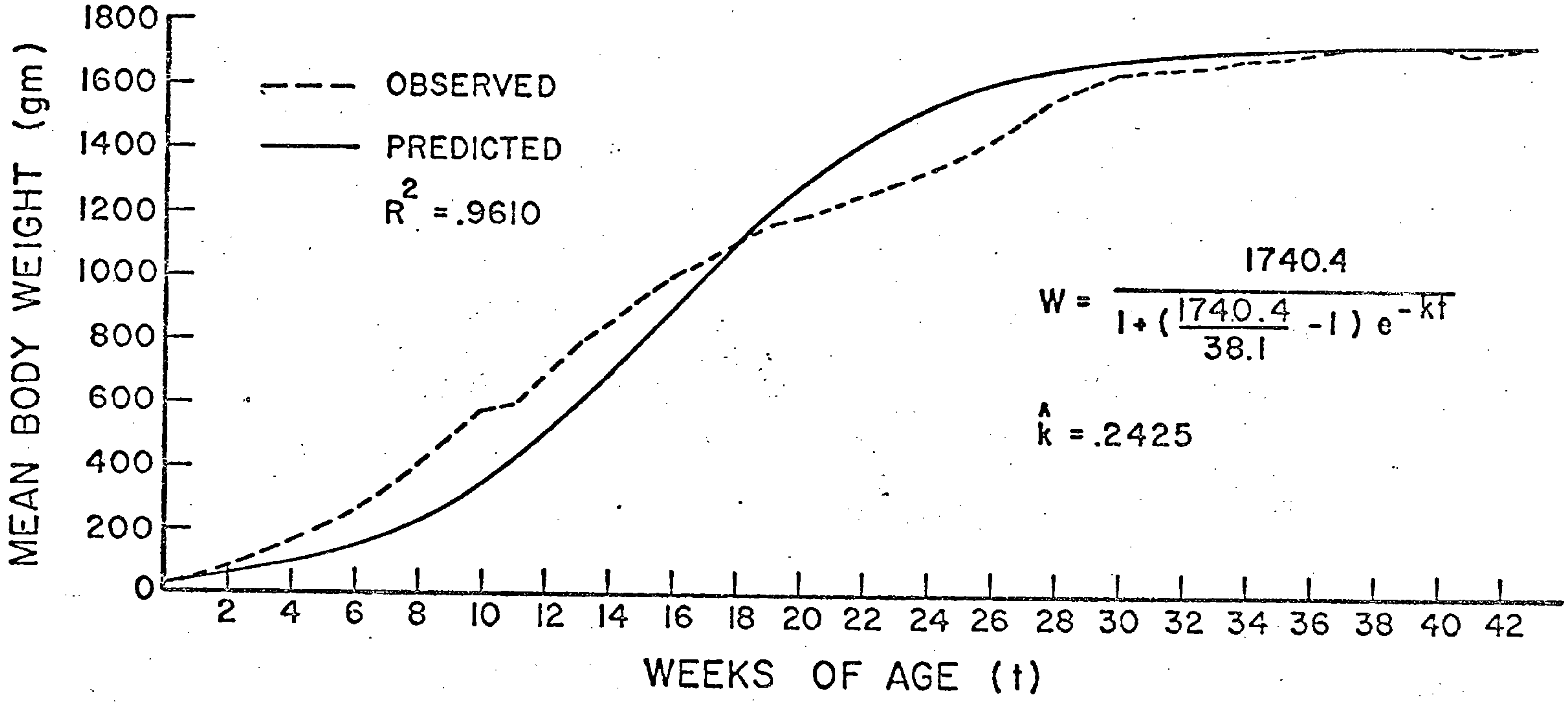


Figure 2.8. The Logistic Curve Fit to Maximum Mean Weights of White Leghorn Females by Nonlinear Regression

males and 0.2826 vs. 0.2425 for the females.

Based on equation (2.21) the age at the point of inflection was calculated for each population when $t' = 0$. Values for the initial (W_0) and maximum weights (W_∞) were taken from Tables C1 - C4. Appropriate estimates for k were taken from Table 2.5. The estimated values for the age at the inflection point are presented in Table 2.6.

Table 2.6. Estimated Values for Age at the Point of Inflection (t^*) by Nonlinear Regression for Each Population

	Line	
Sex	RIR	WL
Male	14.5	14.2
Female	14.4	15.7

In the RIR line, the males had an estimated value for the age at the inflection point that was about the same as the value for the females, namely 14.5 vs. 14.4. On the contrary, the females of the WL line had an estimated value for t^* that was larger than the males of that line; the values being 15.7 vs. 14.2.

In comparing the estimates of both parameters of the logistic function based on order statistics and nonlinear regression procedures both the absolute and relative values of the estimates should be considered. With regard to the intrinsic growth rate constant the estimates from the method of order statistics were larger in each population than estimates from the nonlinear regression procedure. For the age at the point of inflection, however, estimates from nonlinear regression were larger than estimates from order statistics. Therefore, the results should be interpreted accordingly when interest is in the absolute values of the population parameters.

More important, though, is comparing the relative estimates by the two methods. For both parameters the ranking of the populations were the same. Thus, it appears that when interest is in the realtive estimates of the population parameters either method may be used. It is important to note, however, that the magnitude of the standard errors of the mean of the growth rate estimates are smaller using the nonlinear regression technique than with the order statistics method. The reason for the smaller standard error is that it is a function of the length of the time interval; a result of the errors being cumulative (Mandel, 1957). Thus, one of the basic assumptions of the regression procedure, independent measurements, was violated. The validity of the using of the regression analysis, then, is open to question since it is well known that the correlation between successive body weights is high (see Chapter I). Some work has been done regarding the effects of correlated observations on statistical tests when using a polynomial regression model (Hoel, 1964). Little, if anything, is known about the effects on the parameter estimates when using nonlinear regression. This should be a fruitful area of further study.

Nonlinear Regression Relaxing Constraints on Initial and Maximum Mean Weights. Notwithstanding the violation of the assumption of independent measurements, further studies were made using the procedure of nonlinear regression to estimate the parameters of the logistic function when the constraints of fixed initial and maximum mean weights were relaxed. The observed data were weekly means of each population measured during the entire experiment, i.e. up to age 45 weeks (Table C5). The graphs of the observed and predicted growth curves are presented for each population in Figures 2.9 - 2.12.

Table 2.7 contains observed estimated values of the logistic parameters in each population and comparisons can be made between the observed and predicted values. The observed initial and maximum weights are hatching weight and largest body weight achieved up to 45 weeks of age, respectively. The observed weight at the inflection point is the average weight achieved during the period of maximum gain. For example, in the RIR females, maximum gain was made during period 12 and the observed weight at inflection was calculated to 1/2 (954.2 + 1096.4) = 1025.3. The observed time at the point of inflection was taken as the age interval when maximum gain was made, e.g. 12-13 weeks of age for RIR females. The predicted weight at the inflection point was calculated from the theory as $W_\infty/2$ and the time at the point of inflection was predicted from equation 2.21.

Of interest is the comparison of the values obtained for k by regression without constraints with those values from the regression procedure with constraints (see Table 2.8).

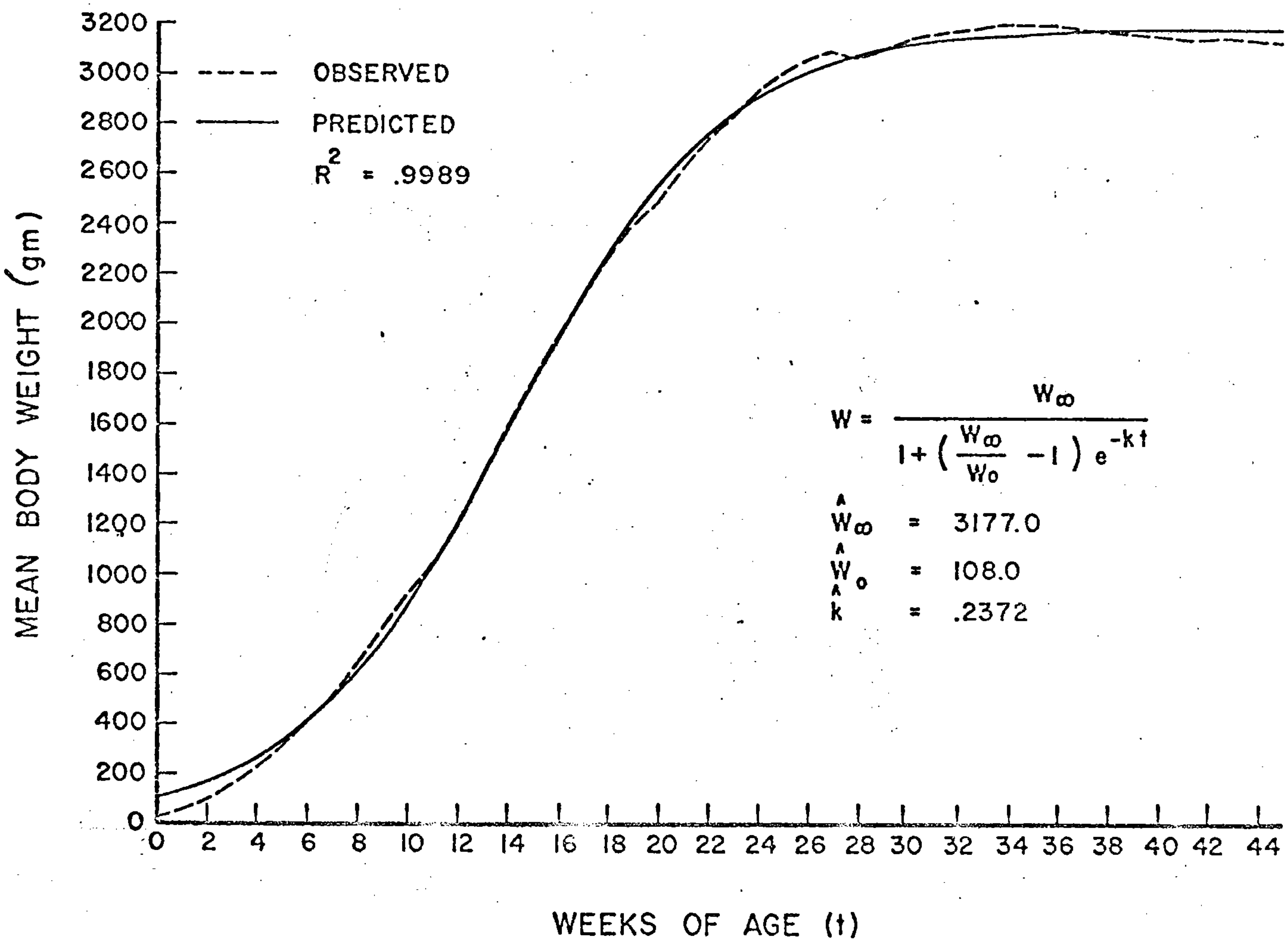


Figure 2.9. The Logistic Curve Fit to Mean Weights of Rhode Island Red Males by Nonlinear Regression

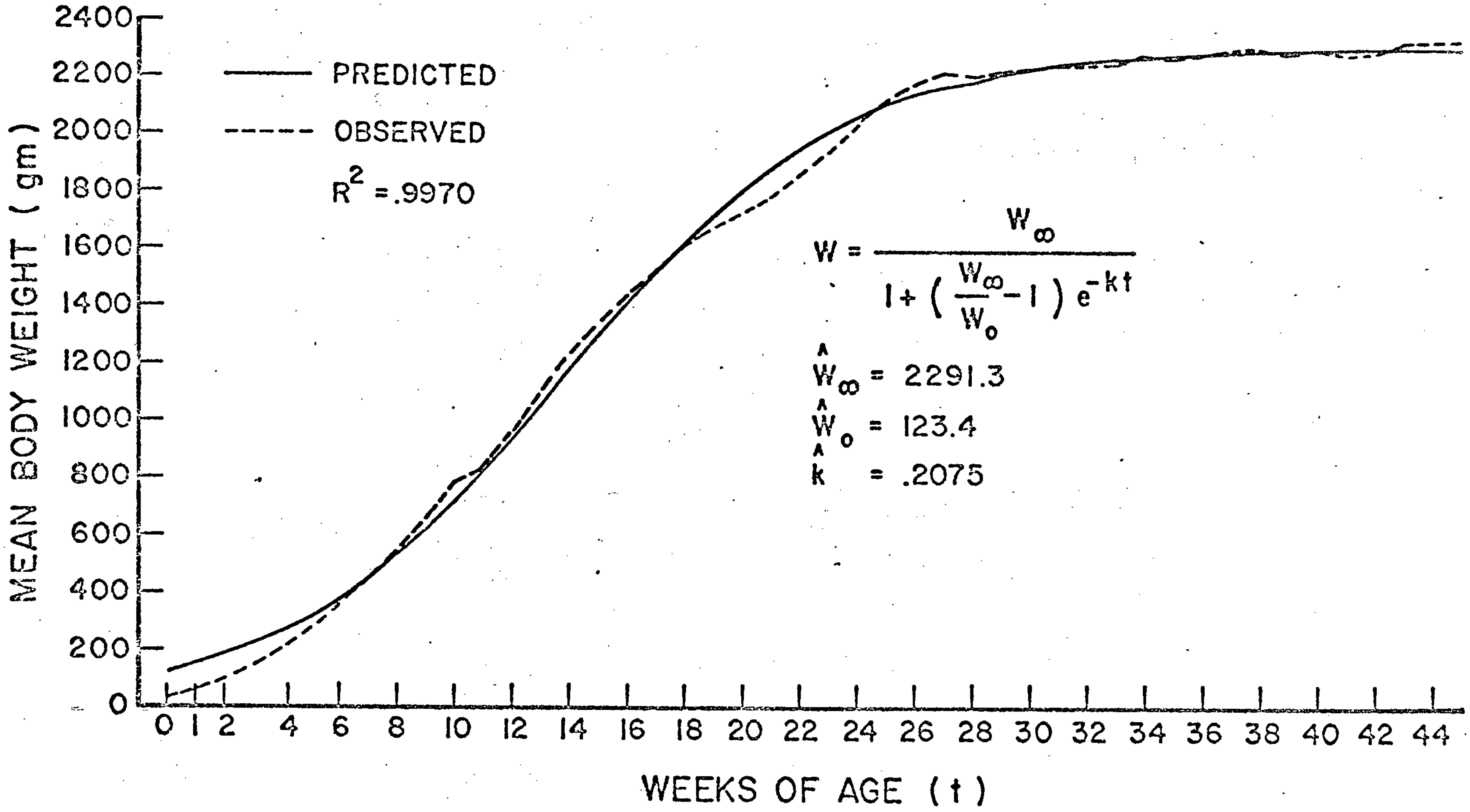


Figure 2.10. The Logistic Curve Fit to Mean Weights of Rhode Island Red Females by Nonlinear Regression

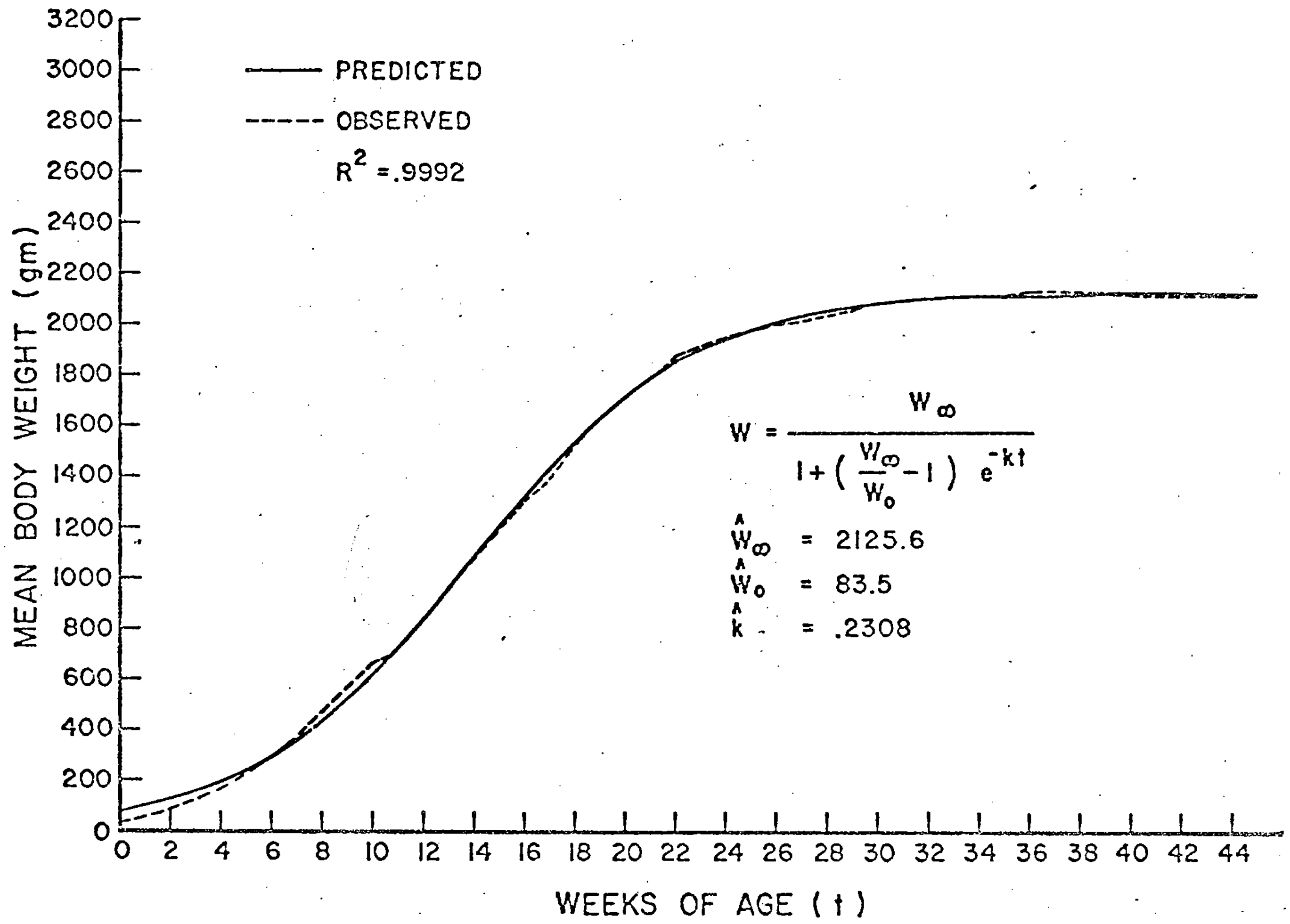


Figure 2.11. The Logistic Curve Fit to Mean Weights of White Leghorn Males by Nonlinear Regression

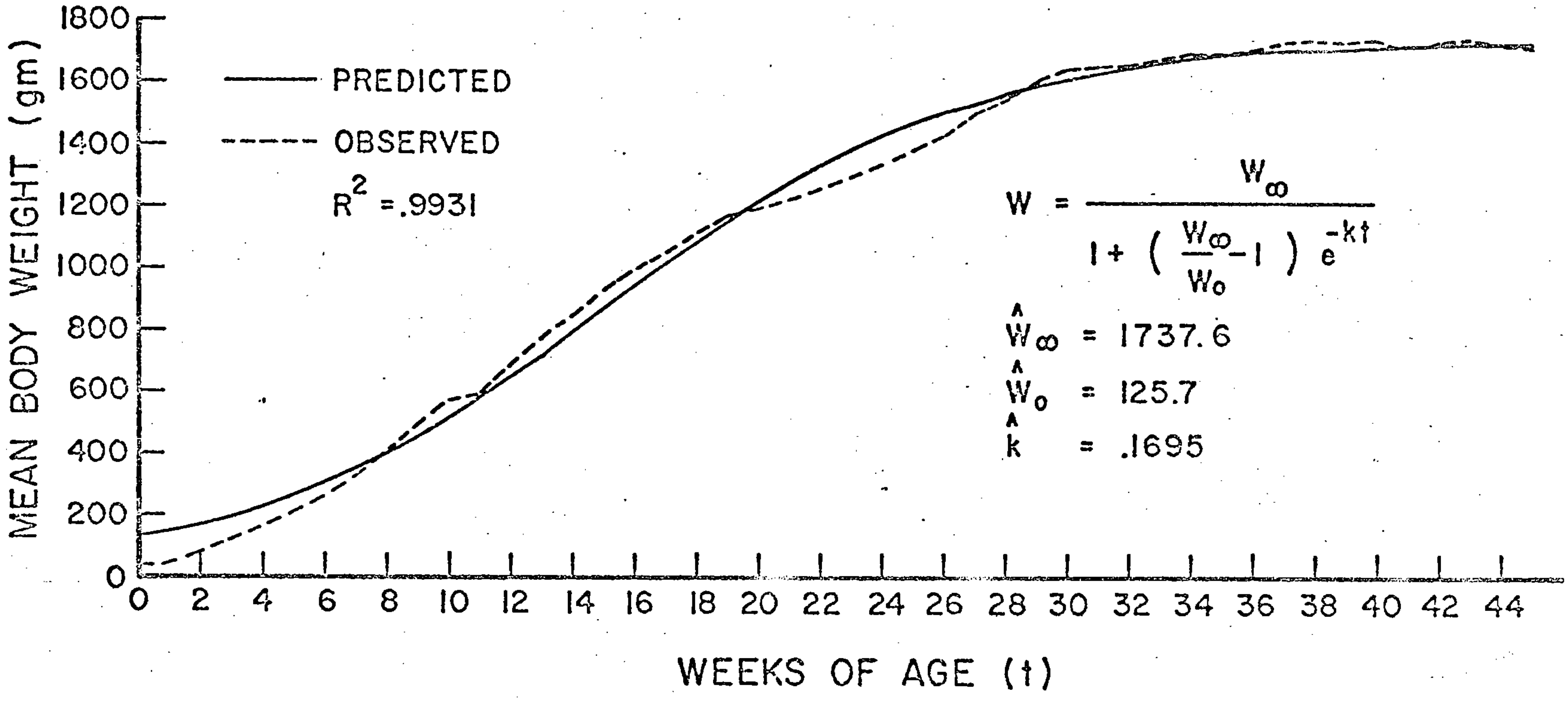


Figure 2.12. The Logistic Curve to Mean Weights of White Leghorn Females by Nonlinear Regression

Table 2.7. Estimates of the Logistic Parameters by Nonlinear Regression With No Constraints for Each Population

RIR Line

Parameter	♂♂		♀♀	
	Obs.	Pred.	Obs.	Pred.
Initial wt. (W_o)	38.8	108.0 ± 5.21	38.7	123.4 ± 7.81
Maximum wt. (W_∞)	3192.0	3177.0 ± 9.77	2320.0	2291.3 ± 11.96
Growth rate (k)	---	.2372 ± .0036	---	.2075 ± .0049
Wt. at inflection	1394.0	1588.5	1025.3	1145.65
Time at inflection (weeks of age)	12-14	14.1	12-13	13.8
R^2	.9989		.9970	

WL Line

Parameter	♂♂		♀♀	
	Obs.	Pred.	Obs.	Pred.
Initial wt. (W_o)	37.9	83.5 ± 3.17	38.1	125.7 ± 9.91
Maximum wt. (W_∞)	2129.2	2125.6 ± 5.46	1740.4	1737.6 ± 16.06
Growth rate (k)	---	.2308 ± .0029	---	.1695 ± .0058
Wt. at inflection	898.4 - 1467.8	1062.8	735.9	868.8
Time at inflection (weeks of age)	12-13 17-18	13.8	12-13	15.1
R^2	.9992		.9931	

Table 2.8. Estimates of the Intrinsic Growth Rate Constant (k) from Nonlinear Regression With and Without Constraining Initial and Maximum Weight

Population	With Constraints	Without Constraints
RIR Males	0.3089 ± .0039	0.2372 ± .0036
RIR Females	0.2826 ± .0047	0.2075 ± .0049
WL Males	0.2834 ± .0031	0.2308 ± .0029
WL Females	0.2425 ± .0049	0.1695 ± .0058

Although the k values for each population had the same ranking, the values obtained without constraints were lower than when initial and maximum weights were fixed, for example 0.1695 vs. 0.2425 in the case of the WL females. Thus, it appears that the amount of restrictions one puts on a function plays a large role in determining the absolute value of the estimate but not in its relative value. This is an essential point to remember when the heritability of k is estimated since it is the relation among k values in the population that is important.

Parameter Estimates of the Logistic Function Based on Individual Weights

As stated earlier, one of the objectives of this experiment was to test the hypothesis that the intrinsic growth rate constant was an inherited characteristic. To estimate the heritability of k, individual values, based on weekly body weights of each chicken, were obtained using the order statistics procedure. In addition to individual estimates of k, values for the initial and maximum weights and μ were obtained. The means of the individual estimates of k, μ, and the maximum weights are presented in Table 2.9.

Table 2.9. Means of Individual Estimates of the Growth Rate (k), the Age at Inflection Point (μ), and the Initial and Maximum Weights for Each Population

Populations	Growth Rate (k)	Age at Infl. Pt. (weeks)	Initial Wt. (gm)	Max. Wt. (gm)
RIR Males	0.4047 ± .0316	15.4 ± 0.88	38.8	3231.3
RIR Females	0.3387 ± .0355	15.6 ± 1.19	38.7	2382.6
WL Males	0.4034 ± .0363	15.1 ± 1.00	37.9	2156.8
WL Females	0.3029 ± .0267	16.6 ± 1.36	38.1	1780.9

A comparison can be drawn between the mean of the individual estimates (Table 2.9) and estimates based on the weekly means (Tables 2.3 and 2.4) from order statistics. Of particular interest is the growth rate constant (a function of the standard deviation) and the age at the inflection point (a function of the mean) because they describe the logistic distribution. For the age at the point of inflection the difference between the two estimates for males was 1.2 weeks for both the RIR and WL line. For the females, however, the differences were 1.6 and 1.5 weeks for the RIR and WL lines, respectively. With respect to the growth rate constant, the difference between the two estimates for males was .0207 and .0203, while the differences in the case of the females was .0336 and .0213 for the RIR and WL lines, respectively. Thus, the absolute values differed depending on whether individuals or means were used, with the discrepancies being larger for females than for males. In either case, these results indicate that if interest is in absolute values, caution should be used when interpreting the results. With regard to the relative values of the estimates, the ranking of the populations was the same for all parameters except the age at the point of inflection which had one change in rank.

Heritability Estimates of the Logistic Parameters

Of particular interest in this research is the estimate of the heritability of the intrinsic growth rate constant, $\underline{k}$. A knowledge of the heritability is essential for prediction of genetic gain when the population is under selection for that trait; for example, selection for a high intrinsic growth rate.

The heritability estimates are based on variance components from an analysis of variance. One of the assumptions of an analysis of variance, if tests of significance are of interest, is that the variable to be analyzed ($\underline{k}$ in this case) is normally distributed in the population. Figures D1 - D4 (Appendix D) show the frequency distribution of $\underline{k}$ values within each population. Although no statistical test was performed to test normality, since the numbers were not very large, the distributions appear near enough to normal to warrant analyzing the data without transformation. The analysis of variance of the variable intrinsic growth rate constant, for each population is presented in Table 2.10.

Table 2.10. Nested Analyses of Variance for the Intrinsic Growth Constant (k) for Each Population*

	RIR				WL			
	♂♂		♀♀		♂♂		♀♀	
Source	d.f.	M.S.	d.f.	M.S.	d.f.	M.S.	d.f.	M.S.
Sires (S)	31	.0013411	31	.0023759	30	.0019057	33	.0015785
Dams(D)/S	18	.0012699	18	.0016754	16	.0009516	17	.0007946
Progeny/D/S	175	.0009086	231	.0010818	117	.0008365	188	.0005524
Total	224		280		163		238	

* Coefficients of Variance Components

	RIR		WL	
Coefficient	♂♂	♀♀	♂♂	♀♀
k_1	4.576	5.512	2.997	4.506
k_2	4.442	5.663	3.730	4.762
k_3	6.951	8.690	5.246	6.958

Table 2.11. Heritability Estimates of the Intrinsic Growth Rate Constant (k) for Each Population

Population	$h^2_S \pm$ s.e.		$h^2_D \pm$ s.e.		$h^2_{S+D} \pm$ s.e.	
RIR Males	0.047	.312	0.316	.379	0.181	.323
RIR Females	0.248	.298	0.339	.324	0.294	.286
WL Males	0.671	.432	0.146	.449	0.408	.402
WL Females	0.617	.380	0.299	.344	0.458	.323

Based on the results in Table 2.10, heritability estimates were calculated for each population. Table 2.11 presents individual heritability estimates of the intrinsic growth rate constant, based on sire (h^2_S), dam (h^2_D) and sire plus dam (h^2_{S+D}) components of variance.

For a more complete understanding of these results, they should be taken together with the percentage of variation attributed to the sire, dam and progeny components of variance as presented in Table 2.12. In the RIR line, the dam component accounted for a larger percentage of the total variance than did the sire component of variance. However, in the WL line, the opposite was true. The sire component was larger than the dam component of variance. In all cases, the variance among full sib progeny (error component of variance) accounted for at least 77 percent of the total variation among $\underline{k}$ values.

The results of Tables 2.11 and 2.12 indicate that in both sexes of the RIR and WL lines the trait, intrinsic growth rate constant, is lowly heritable, if it is heritable at all. It is obvious that none of the 12 estimates of heritability obtained for these four populations, are really different from zero.

The importance of the age at the point of inflection should not be overlooked. The age at the inflection point is related to the age when the gain in weight is the largest. It is conceivable, then, that a selection program could be initiated to decrease the age at the point of inflection. This, in effect, would lower the age when the individual achieves its maximum gain. To predict the genetic gain in the age at the point of inflection, an estimate of the heritability is required. Individual heritability estimates of the age at the point of inflection were calculated from the analyses of variance presented in Table 2.13.

Table 2.12. Estimates of Sire, Dam and Progeny Components of Variance and Percentage of Total Phenotypic Variation Attributed to Each for the Intrinsic Growth Rate Constant

Component	Variance Estimate	Percentage Variation
RIR ♂♂		
Sire	.0000117638	1.1772
Dam	.0000789574	7.9012
Progeny	.0009085857	90.9216
RIR ♀♀		
Sire	.0000787385	6.2085
Dam	.0001076963	8.4918
Progeny	.0010817982	85.2997
WL ♂♂		
Sire	.0001765235	16.7886
Dam	.0000384004	3.6522
Progeny	.0008365213	79.5592
WL ♀♀		
Sire	.0001106913	15.4405
Dam	.0000537429	7.4967
Progeny	.0005524551	77.0628

Table 2.13. Nested Analyses of Variance for Age at the Point of Inflection (μ) for Each Population*

	RIR				WL			
	♂♂		♀♀		♂♂		♀♀	
Source	d.f.	M.S.	d.f.	M.S.	d.f.	M.S.	d.f.	M.S.
Sires (S)	31	1.1866	31	3.2204	30	1.9067	33	4.4967
Dams (D)/S	18	1.3691	18	1.9525	16	0.9207	17	1.6338
Progeny/D/S	175	0.6324	231	1.1232	117	0.7772	188	1.3990
Total	224		280		163		238	

* See Table 2.10 for coefficients of variance components.

From the results in Table 2.13, heritability estimates were calculated for each population based on sire, dam and sire plus dam components and are presented in Table 2.14.

Table 2.14. Heritability Estimates of the Age at the Point of Inflection (μ) for Each Population

Population	h^2_S ± s.e.		h^2_D ± s.e.		h^2_{S+D} ± s.e.	
RIR Males	-0.120	.409	0.836	.524	0.358	.443
RIR Females	0.404	.340	0.425	.338	0.415	.306
WL Males	0.720	.447	0.190	.452	0.455	.409
WL Females	0.880	.383	0.112	.276	0.496	.283

The results in Table 2.14 indicate that in both sexes of the RIR and WL lines the age at the inflection point is not heritable, based on the magnitude of the standard errors. Thus, it is unlikely that any real decrease in the genotypic mean can be achieved by selection for low age at the point of inflection.

Genetic Correlations Among Logistic Parameters

Genetic correlations, estimated from individual values, between the intrinsic growth rate constant ($\underline{k}$) and the age at the inflection point were of interest. These are the parameters in equation (2.35). Along with the heritabilities of the traits, the genetic correlation is important in predicting the correlated genetic change in one trait when selection is applied to the other trait. The genetic correlations, based on sire components of variance and covariance, are presented in Table 2.15.

Table 2.15. Estimated Genetic Correlations Between the Growth Rate Constant ($\underline{k}$) and Age at the Inflection Point ($\underline{\mu}$) for Each Population

	Line	
Sex	RIR	WL
Male	0.0471 ± 0.3129	-0.0053 ± 0.4469
Female	-0.2315 ± 0.6722	-0.3999 ± 0.3077

With the magnitude of the standard errors being so large, one can only say that these genetic correlation estimates are probably not different from zero. This indicates that with any genetic change in the mean of the growth rate constant (k), a correlated genetic change in the age at maximum gain should not be expected.

If selection could be applied to the population with regard to the intrinsic growth rate constant, it would be of interest to determine whether or not correlated changes in the initial and maximum weights would occur. Therefore, genetic correlations among these traits were studied. These are the parameters in equation (2.19).

Using the sire components from an analysis of individual values, the genetic correlations among initial weight, maximum weight and the intrinsic growth rate constant were calculated. The correlations are presented in Table 2.16. Based on the magnitude of the standard errors the results indicate that there is no genetic relationship among the logistic parameters of equation (2.19). A possible exception to this generalization is the correlation between the growth rate and initial weight in the RIR line. That correlation was estimated to be -0.9135 ± .2186. It should be noted, however, that the estimate of the standard error is bad when the correlation is close to one (Robertson, 1959). Therefore, these results should be interpreted cautiously because of the small population sizes and large standard errors of the estimates.

Table 2.16. Estimates of Genetic Correlations Among Logistic Parameters[a]

RIR Line

Parameter	W_∞	W_o	k
Maximum wt. (W_∞)	———	.1464(.3472)	1.9329(c)
Initial wt. (W_o)	-.1094(.3903)[b]	———	-.9135(.2186)
Growth rate (k)	.1115(.5614)	-.4298(.4814)	———

WL Line

Parameter	W_∞	W_o	k
Maximum wt. (W_∞)	———	(d)	-.1631(.6547)
Initial wt. (W_o)	(d)	———	(d)
Growth rate (k)	(d)	(d)	———

[a] Correlations above diagonal for males and below diagonal for females.

[b] Numbers in parentheses are standard errors.

[c] Standard error is not calculated when estimate of correlation is greater than ± 1.

[d] Correlation not calculated because of a negative estimate for genetic variance.

SUMMARY AND CONCLUSIONS

Growth has been correlated with different measurements on several biological levels. For example, on the biochemical level, RNA and DNA contant have been measured to determine differences in growth. At a higher level, protein metabolic activity has been physiologically related to body size. At the population level, the genetic and biometrical properties of the growth pattern have been examined by studying the parameters of a mathematical growth function which uniquely describes the growth curve of each individual in the population and consequently the population.

It was the primary purpose of this study to determine the parameters of a mathematical function of growth which best fit the body weight curve of four specific populations of chickens from hatching to 45 weeks of age. The relationships among the parameters of the growth function were also the subject of the study. Included among these parameters is an intrinsic growth rate constant, distinct from the average rate of change in body weight. The intrinsic growth rate constant expresses the rate of gain as a function of the weight at a specific time and the gain yet to be made; for this reason, it was chosen to be studied. It was also the purpose of this research to test the hypothesis that the intrinsic growth rate constant is an inherited characteristic.

Weekly individual body weights were taken on 909 chickens of both sexes from two control lines, the Rhode Island Red (RIR) and White Leghorn (WL), maintained by random mating. The logistic function was chosen from among those growth formulae expressing the rate of gain as a function of the intrinsic growth rate constant. The parameters of the logistic function were estimated from the weekly means of body weights by the methods of order statistics and nonlinear regression. Order statistics was also used to estimate the logistic parameters from individual body weights. The four parameters estimated were the initial and maximum weights, the intrinsic growth rate constant and the age at the point of inflection. Interest was centered around the latter two parameters since they determine the scale and location of the curve, however, their relationship with the former two parameters was also of interest.

By using the methods of nonlinear regression and order statistics, comparisons could be made between the estimates of the parameters by each method. The method of order statistics (based on maximum likelihood estimation) required constraints on the theoretical values such that the lower asymptote was zero and the upper asymptote was fixed at 1.00. Thus, the data points were transformed and expressed as a fraction of maximum weight. The estimates of the intrinsic growth rate constant ($\underline{k}$) and the age at the inflection point ($\underline{\mu}$) were obtained for each population. The estimates of $\underline{k}$ were 0.4254 and 0.4237 for the males, and for the females were 0.3723 and 0.3242 in the RIR and WL lines, respectively. The results indicated that the males had a larger growth rate than the females of the same line. The RIR line had a larger value for the rate constant than the WL line within a sex.

As the theory dictated the predicted curves were symmetrical about the mean ($\underline{\mu}$) or the age at the inflection point. The estimates of $\underline{\mu}$ were 14.2 and 13.9 weeks for the males, while for the females the values were 14.0 and 15.1 weeks in the RIR and WL lines, respectively. Comparisons of the estimated age at the inflection point with the observed age at maximum gain indicated that the logistic function described the growth of the males better than the females.

To compare the nonlinear regression procedure with the method using order statistics, only those mean weights up to the observed maximum were used. In addition, constraints were applied such that the predicted regression line was forced to go through both the observed initial and maximum mean weights. The maximum mean weight up to 45 weeks of age occurred at 34 and 37 weeks of age in the RIR and WL males and at 45 and 43 weeks for the RIR and WL females, respectively. Estimates of the intrinsic growth rate constant ($\underline{k}$) using the method of nonlinear regression were 0.3038 and 0.2834 for the males and for the females were 0.2826 and 0.2425 for the RIR and WL lines, respectively. In comparing the two methods with respect to the $\underline{k}$ values, the method of order statistics yielded larger estimates than the values from the nonlinear regression procedure. However, the ranking of the populations were the same in both methods. It is important also to note that the magnitude of the standard error of the means of the estimates of the growth rate were smaller using the nonlinear regression approach than with the order statistics technique. A possible explanation for this is that the assumptions of the regression procedure, homogeneous variances over time and independent measurements, were violated. The extent to which the violations played a role was not determined.

Nevertheless, further studies were made using the procedure of non-linear regression to estimate the parameters of the logistic function when the constraints of fixed initial and maximum mean weights were relaxed. With reference just to the growth constant (k) the estimates were 0.2372 and 0.2308 for the males and for the females the values were 0.2075 and 0.1695 for the RIR and WL lines, respectively. Of interest is the comparison of the values obtained for k by regression without constraints to those values from the regression procedure with constraints.

Although the k values for each population had the same ranking, the values obtained without constraints were smaller than when initial and maximum mean weights were fixed. Thus, the amount of restrictions one puts on a function plays a large role in determining the absolute value of the estimate, and therefore the shape of the curve, but not in its relative value. This is an essential point, since it is the relation among k values in the population that is important when the heritability of k is estimated.

As stated earlier, one of the objectives of this experiment was to test the hypothesis that the intrinsic growth rate constant was an inherited characteristic. To estimate the heritability of k, individual values, based on individual weekly body weights, were obtained using the order statistics procedure. In addition to individual estimates of k, values for the initial and maximum weights and μ were obtained. First, however, a comparison was made between the mean of the individual estimates and the estimates based on the weekly means from order statistics. Of particular interest was the intrinsic growth rate constant and the age at the inflection point since they described the logistic distribution. With respect to the growth rate constant, the values for the males were 0.4047 and 0.4034, while for the females the values were 0.3387 and 0.3029 for the RIR and WL lines, respectively. For the age at the inflection point the estimates for the males were 15.4 and 15.1 weeks and for the females were 15.6 and 16.6 weeks in the RIR and WL lines, respectively. In all populations, the means of the individual estimates of the growth rate constant were smaller than the estimates based on weekly means. For the age at the inflection point, the estimates based on weekly means were smaller than the means of the individual estimates, for all populations.

Thus, the absolute values differed depending on whether individuals or means were used. These results indicated that if interest is centered on absolute values, care should be taken when interpreting the results. With regard to the relative values of the estimates, the ranking of the populations was the same for both parameters except the age at the inflection point which had one change of rank.

The heritability of the growth rate constant, $\underline{k}$, was estimated from components of variance from a nested analysis of variance. Estimates based on the correlation among full sibs were 0.18 and 0.41 for the males and for the females the values were 0.29 and 0.46 in the RIR and WL lines, respectively. Based on the magnitude of the standard errors, the results indicated that in both sexes of the RIR and WL lines the intrinsic growth rate constant was not heritable.

The heritability estimates of the age at the inflection point were also calculated for each population. The estimates from the correlation among full sibs were 0.36 and 0.46 for the males, and 0.42 and 0.50 for the females of the RIR and WL lines, respectively. Again, the standard errors were of such magnitude that the results showed that the age at the inflection point was not heritable. Thus, it is unlikely that any predictable change in the genetic mean would occur if selection were applied to either trait.

To determine the genetic association between the intrinsic growth rate constant (k) and the age at the inflection point, genetic correlations based on sire components were estimated in each population. The magnitude of the standard errors was large relative to the estimates so that the genetic correlations were probably not different from zero. This indicated that with any genetic change in the mean of the growth rate constant (k), a correlated genetic change in the age at maximum gain would not be expected.

Finally, it was of interest to determine whether or not a correlated change in the initial and maximum weights would occur if selection pressure were applied to the population with respect to the growth rate constant. Therefore, genetic correlations among these traits were examined. Based on the magnitude of the standard errors, the results indicated that there were no genetic relationships among these parameters.

It is concluded, therefore, that any attempt to genetically change the shape of the growth curve of these chickens, say by selecting for high intrinsic growth rate constant or low age at the inflection point, would probably not be successful. If selection could be practiced, no correlated change in the initial or maximum weight achieved would be expected.

RECOMMENDATIONS

To overcome the objection that the nonlinear regression analysis is invalid due to a high correlation among measurements, an alternative solution will be proposed to estimate the logistic parameters.

Mandel (1957) suggested that in cases of cumulative errors (as in weekly body weights) first differences should be taken and an analysis done on the transformed data. This method also partially solved the problem of increasing variances over time. With regard to the present study, the analysis would be a nonlinear regression on weekly gain in weight. The rate of gain formula for the logistic function is:

$$\frac{\Delta W_x}{\Delta x} = k\, W_x \left(\frac{W_\infty - W_x}{W_\infty}\right) \quad .$$

By substituting equation (2.19) into the above formula (when $x = t$), the rate of gain is a function of the initial and maximum weights and the intrinsic growth rate constant. Using this function of three parameters the nonlinear regression analysis could be performed on weekly mean body weights of each population. An analysis of this type was performed on weekly mean gains and the results showed that the populations had the same rank, with regard to the growth rate constant, as when the analysis was done on body weights. The absolute values were lower in the analysis of mean gains, but the standard errors were three to five times higher than in the analysis of mean weights. This reflects lower correlation among gains than among weights.

Based on the evidence that the variation in intrinsic growth rate values was mainly due to environmental sources, some recommendation is necessary for planning future research in this area. Some environmental variation is due to the effect of temperature changes which occur throughout the life cycle of the individual. Some variation is due to effects as, for example, when the females reach sexual maturity and the ovary suddenly increases in size. The latter type of variation cannot be easily controlled but can be used to adjust the data in an appropriate way, perhaps through an analysis of covariance. The temperature variation can be controlled by using constant temperature and/or humidity chambers. These two ways, at least, should allow the researcher to remove extraneous variation and obtain a more reliable estimate of the heritability.

Finally, under a different set of experimental conditions it is possible that other growth functions, e.g. the Gompertz function, could fit the growth curve as well or better than the logistic did. Further study in comparing the functions is also recommended.

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APPENDIX A

SUPPLEMENTARY TABLES, CHAPTER I

Table A1. Population Structure for Rhode Island Red Males

Sire No.	Dam. No.	Family Total
1	1	6[a]
1		6[b]
2	2	4
2		4
3	3	5
3	4	4
3	5	4
3		13
4	6	5
4		5
5	7	5
5		5
6	8	5
6	9	3
6	10	3
6		11
7	11	8
7		8
8	12	4
8		4
9	13	2
9		2
10	14	3
10		3
11	15	4
11	16	3
11	17	5
11		12
12	18	4
12		4
13	19	3
13		3
14	20	6
14		6
15	21	4
15		4
16	22	4
16		4
17	23	4
17	24	5
17		9

Sire No.	Dam No.	Family Total
18	25	2
18		2
19	26	5
19		5
20	27	5
20	28	7
20		12
21	29	4
21	30	5
21		9
22	31	4
22		4
23	32	4
23	33	5
23	34	5
23		14
24	35	4
24	36	3
24		7
25	37	6
25	38	7
25		13
26	39	5
26	40	3
26		8
27	41	2
27		2
28	42	7
28	43	7
28	44	6
28		20
29	45	7
29		7
30	46	3
30		3
31	47	4
31	48	3
31		7
32	49	4
32	50	5
32		9

[a] dam family total; [b] sire family total

Table A2. Population Structure for Rhode Island Red Females

Sire No.	Dam No.	Family Total
1	1	2[a]
1		2[b]
2	2	7
2		7
3	3	6
3	4	7
3	5	4
3		17
4	6	5
4		5
5	7	6
5		6
6	8	4
6	9	11
6	10	5
6		20
7	11	7
7		7
8	12	6
8		6
9	13	4
9		4
10	14	3
10		3
11	15	7
11	16	7
11	17	7
11		21
12	18	8
12		8
13	19	7
13		7
14	20	6
14		6
15	21	4
15		4
16	22	3
16		3
17	23	8
17	24	7
17		15
18	25	7
18		7
19	26	6
19		6
20	27	4
20	28	6
20		10
21	29	7
21	30	8
21		15
22	31	6
22		6
23	32	5
23	33	5
23	34	3
23		13
24	35	5
24	36	7
24		12
25	37	4
25	38	6
25		10
26	39	2
26	40	5
26		7
27	41	7
27		7
28	42	5
28	43	3
28	44	3
28		11
29	45	6
29		6
30	46	3
30		3
31	47	5
31	48	5
31		10
32	49	9
32	50	8
32		17

[a] dam family total; [b] sire family total

Table A3. Population Structure for White Leghorn Males

Sire No.	Dam No.	Family Total
1	1	4[a]
1		4[b]
2	2	4
2		4
3	4	3
3	5	3
3		6
4	6	4
4	7	6
4		10
5	8	1
5		1
6	9	3
6	10	2
6		5
7	11	6
7		6
8	12	2
8	13	5
8		7
9	14	5
9		5
10	15	6
10		6
11	16	5
11	17	5
11	18	2
11		12
12	19	3
12	20	2
12		5
13	21	4
13	22	3
13		7
14	23	4
14		4
15	24	3
15		3
16	25	2
16	26	4
16	27	1
16		7
17	28	2
17	29	1
17	30	2
17		5
18	31	6
18		6
19	32	1
19		1
20	33	5
20		5
21	34	5
21		5
22	35	2
22	36	5
22	37	5
22		12
23	38	4
23		4
25	41	2
25		2
26	42	2
26		2
27	43	4
27		4
28	44	7
28		7
30	46	2
30		2
31	47	4
31	48	3
31		7
32	49	3
32	50	4
32		7
34	52	3
34		3

[a] dam family total; [b] sire family total

Table A4. Population Structure for White Leghorn Females

Sire No.	Dam No.	Family Total
1	1	6[a]
1		6[b]
2	2	4
2	3	4
2		8
3	4	5
3	5	2
3		7
4	6	8
4	7	7
4		15
5	8	8
5		8
6	9	4
6	10	3
6		7
7	11	3
7		3
8	12	3
8	13	6
8		9
9	14	4
9		4
10	15	6
10		6
11	16	5
11	17	7
11	18	3
11		15
12	20	5
12		5
13	21	3
13	22	5
13		8
14	23	4
14		4
15	24	7
15		7
16	25	7
16	26	7
16	27	6
16		20
17	28	4
17	29	3
17	30	5
17		12
18	31	5
18		5
19	32	3
19		3
20	33	3
20		3
21	34	6
21		6
22	35	6
22	36	4
22	37	5
22		15
23	38	5
23		5
24	39	2
24		2
25	40	3
25	41	2
25		5
26	42	5
26		5
27	43	2
27		2
28	44	5
28		5
29	45	8
29		8
30	46	4
30		4
31	47	6
31	48	4
31		10
32	49	4
32	50	3
32		7
33	51	6
33		6
34	52	4
34		4

[a] dam family total; [b] sire family total

Table A5. Purdue Poultry Farm - All Mash Rations

Ingredient	Developer Ration[a] (1-158 days of age) Lbs.	Layer Ration (159-315 days of age) Lbs.
Gr. yellow corn (No. 2)	716.74	636.20
Soybean oil meal (50% pro)	145.15	145.15
Alfalfa meal (dehy-17% pro)	22.68	22.68
Fish meal (60% pro)	---	9.07
Meat and Bone Scrap (50%pro)	---	22.68
Dicalcium phosphate (18% phos)	16.78	12.70
Gr. limestone (95% Cal. Carb.)	9.52	52.62
Iodized salt	4.08	4.08
Manganese sulfate	.45	.45
Stabilized grease	---	9.07
Zinc oxide	.07	.07
Stabilized Vitamin A (10,000 USP/gm)	.23	.45
Vitamin D_3 (30,000 ICU/gm)	.04	.04
Riboflavin (20 gm/lb)	.04	.09
Pantothenic acid (8 gm/lb)	.23	.45
Niacin (50%)	.02	---
Vitamin E (20,000 IU/lb)	.04	.04
Vitamin B_{12} (20 mg/lb)	.18	.23
Menadione S.B. (16 gm/lb)	.04	.04
[b]Amprol	+	---
[c]Ethoxyquin	---	+
Total	916.29	916.11

[a] Supplemented with oyster shells when birds were 140 to 158 days of age

[b] 0.0125% amprolium

[c] 0.0125% ethoxyquin

Calculated Analysis:

Protein %	15	16
Fat	3.1	3.9
Fiber	2.7	2.6
Calcium	1.0	8.0
Avail. Phos.	0.44	0.5
Metab. Energy	1389	1312

Table A6. Means, Standard Deviations and Coefficients of Variation of Weekly Body Weights for Rhode Island Red Males

Age (wks.)	Mean Weight (gm)	Standard Deviation (gm)	Coefficient of Variation (%)
0	38.8	4.05	10.4
1	60.6	7.11	11.7
2	99.7	16.89	16.9
3	159.0	30.84	19.4
4	227.0	43.64	19.2
5	307.6	57.88	18.8
6	406.8	74.67	18.4
7	499.4	91.28	18.3
8	639.2	109.92	17.2
9	788.0	127.04	16.1
10	926.5	143.58	15.5
11	1027.8	158.01	15.4
12	1193.8	175.14	14.7
13	1394.5	191.33	13.7
14	1593.6	208.85	13.1
15	1780.8	227.54	12.8
16	1951.5	247.00	12.6
17	2081.8	261.44	12.6
18	2249.8	277.08	12.3
19	2384.2	285.79	12.0
20	2475.7	297.18	12.0
21	2602.0	310.91	11.9
22	2733.0	323.42	11.8
23	2831.9	342.89	12.1
24	2921.5	356.67	12.2
25	2993.7	362.14	12.1
26	3049.1	361.09	11.8
27	3080.6	361.33	11.7
28	3051.7	354.23	11.6
29	3084.7	352.99	11.4
30	3129.2	354.75	11.3
31	3150.4	353.20	11.2
32	3166.7	354.75	11.2
33	3179.3	352.49	11.1
34	3192.0	355.97	11.2
35	3185.5	351.96	11.0
36	3188.4	347.58	10.9
37	3175.8	349.28	11.0
38	3161.3	346.31	11.0
39	3158.3	342.00	10.8
40	3149.4	338.92	10.8
41	3133.3	339.25	10.8
42	3131.7	336.72	10.8
43	3139.4	342.42	10.9
44	3136.6	345.71	11.0
45	3118.3	338.68	10.9

Table A7. Means, Standard Deviations and Coefficients of Variation of Weekly Body Weights for Rhode Island Red Females

Age (wks.)	Mean Weight (gm)	Standard Deviation (gm)	Coefficient of Variation (%)
0	38.7	3.97	10.3
1	60.0	7.34	12.2
2	96.1	15.42	16.0
3	146.5	25.68	17.5
4	207.0	37.49	18.1
5	274.3	51.32	18.7
6	360.7	66.70	18.5
7	445.8	80.28	18.0
8	555.8	98.82	17.8
9	667.6	111.99	16.8
10	779.0	123.68	15.9
11	829.0	126.46	15.2
12	954.2	135.05	14.2
13	1096.4	143.75	13.1
14	1222.7	154.63	12.6
15	1327.3	159.46	12.0
16	1434.5	167.13	11.6
17	1519.3	170.94	11.2
18	1608.1	174.04	10.8
19	1678.0	180.80	10.8
20	1720.6	188.75	11.0
21	1772.8	198.82	11.2
22	1846.8	218.33	11.8
23	1935.1	243.76	12.6
24	2022.8	253.09	12.5
25	2113.0	253.80	12.0
26	2162.8	250.05	11.6
27	2203.5	248.05	11.3
28	2197.3	244.46	11.1
29	2207.1	254.79	11.5
30	2216.4	248.69	11.2
31	2231.3	250.96	11.2
32	2229.8	252.47	11.3
33	2237.9	254.11	11.4
34	2261.1	261.60	11.6
35	2255.9	263.76	11.7
36	2270.2	266.65	11.7
37	2280.0	269.68	11.8
38	2286.3	275.11	12.0
39	2276.6	274.22	12.0
40	2286.2	279.99	12.2
41	2266.2	274.90	12.1
42	2274.2	277.97	12.2
43	2316.3	280.85	12.1
44	2310.7	286.98	12.4
45	2320.0	292.29	12.6

Table A8. Means, Standard Deviations and Coefficients of Variation of Weekly Body Weights for White Leghorn Males

Age (wks.)	Mean Weight (gm)	Standard Deviation (gm)	Coefficient of Variation (%)
0	37.9	4.05	10.7
1	54.8	6.60	12.0
2	85.6	15.20	17.8
3	126.8	26.01	20.5
4	171.5	38.56	22.5
5	226.5	52.83	23.3
6	301.0	68.21	22.7
7	371.8	83.21	22.4
8	476.0	100.52	21.1
9	577.0	112.55	19.5
10	666.6	122.23	18.3
11	717.7	125.52	17.5
12	836.7	128.37	15.3
13	960.1	134.91	14.0
14	1078.5	141.76	13.1
15	1194.7	153.15	12.8
16	1309.5	165.33	12.6
17	1396.8	166.32	11.9
18	1526.8	181.35	11.9
19	1634.2	192.92	11.8
20	1704.3	197.77	11.6
21	1784.9	203.30	11.4
22	1861.0	210.03	11.3
23	1916.5	219.33	11.4
24	1947.1	222.52	11.4
25	1976.8	227.22	11.5
26	1994.0	232.72	11.7
27	2013.8	234.77	11.6
28	2025.9	228.90	11.3
29	2049.4	228.30	11.1
30	2076.2	229.91	11.1
31	2091.2	233.48	11.2
32	2100.4	235.74	11.2
33	2117.8	232.99	11.0
34	2116.0	233.65	11.0
35	2117.3	236.10	11.2
36	2128.7	234.29	11.0
37	2129.2	235.66	11.1
38	2126.6	237.52	11.2
39	2121.3	233.46	11.0
40	2117.1	234.57	11.1
41	2112.3	232.90	11.0
42	2112.0	234.81	11.1
43	2117.3	234.68	11.1
44	2113.6	233.66	11.0
45	2116.2	236.10	11.2

Table A9. Means, Standard Deviations and Coefficients of Variation

Weekly Body Weights for White Leghorn Females

Age (wks.)	Mean Weight (gm)	Standard Deviation (gm)	Coefficient of Variation (%)
0	38.1	3.99	10.5
1	56.0	6.68	11.9
2	86.5	16.45	19.0
3	125.0	27.80	22.2
4	164.5	39.80	24.2
5	211.8	53.96	25.5
6	269.3	68.35	25.4
7	333.9	83.26	24.9
8	411.4	96.95	23.6
9	501.5	108.69	21.7
10	575.7	119.18	20.7
11	596.9	115.77	19.4
12	686.6	116.20	16.9
13	785.2	119.84	15.3
14	856.7	119.68	14.0
15	936.1	125.54	13.4
16	1002.7	128.46	12.8
17	1044.9	128.35	12.3
18	1112.3	129.80	11.7
19	1164.9	130.96	11.2
20	1193.6	133.40	11.2
21	1220.4	134.79	11.0
22	1259.3	137.28	10.9
23	1297.8	146.61	11.3
24	1332.7	156.86	11.8
25	1380.8	173.64	12.6
26	1435.3	191.87	13.4
27	1499.2	203.14	13.5
28	1563.8	203.47	13.0
29	1606.5	208.61	13.0
30	1640.8	210.99	12.8
31	1652.2	209.18	12.7
32	1657.0	206.49	12.5
33	1671.9	211.12	12.6
34	1688.1	215.50	12.8
35	1691.3	216.87	12.8
36	1711.9	220.38	12.9
37	1724.1	223.58	13.0
38	1726.8	226.45	13.1
39	1724.2	224.26	13.0
40	1731.0	225.87	13.0
41	1719.6	229.01	13.3
42	1727.3	226.88	13.1
43	1740.4	230.70	13.2
44	1723.8	227.35	13.2
45	1713.0	219.84	12.8

Table A10. Additive Genetic Variance Estimates of Weekly Body Weights, Based on Sire Plus Dam Components, for Rhode Island Red and White Leghorn Males and Females

Age (wks.)	RIR		WL	
	♂♂	♀♀	♂♂	♀♀
0	24.62	25.08	26.72	23.54
1	40.24	42.66	26.56	42.74
2	141.54	90.04	118.28	220.58
3	453.42	231.22	288.96	537.10
4	1,003.26	463.34	716.48	1,088.48
5	1,568.52	1,219.62	1,748.60	2,129.68
6	2,552.88	2,383.56	2,829.40	3,126.90
7	3,772.68	3,486.58	3,754.36	4,350.14
8	5,589.42	5,501.22	5,262.34	6,344.20
9	7,827.76	7,429.28	6,543.72	8,106.54
10	10,639.94	9,148.88	8,518.32	10,317.82
11	11,400.62	9,442.72	8,020.38	10,393.96
12	14,550.74	11,651.02	9,821.30	9,752.08
13	20,056.82	14,759.04	10,753.32	9,682.90
14	26,374.10	18,872.08	12,629.84	9,832.76
15	35,008.92	20,536.94	13,619.30	11,012.42
16	43,191.70	22,947.88	15,043.16	11,466.64
17	49,339.12	24,330.62	14,780.38	11,361.68
18	55,036.86	24,910.52	17,823.22	12,433.06
19	61,295.78	27,294.84	22,269.58	12,680.18
20	68,788.74	30,646.96	24,410.72	13,624.42
21	74,246.50	34,634.50	27,766.18	14,147.50
22	77,789.66	39,679.08	30,424.00	15,365.32
23	85,818.18	48,246.14	33,759.54	19,111.32
24	91,940.04	48,985.98	35,502.38	22,093.74
25	92,448.92	50,416.30	36,042.38	26,400.12
26	93,644.98	51,420.04	38,387.30	31,207.42
27	96,825.26	52,472.24	37,620.52	33,650.84
28	93,396.72	51,790.18	34,479.52	33,514.92
29	93,509.46	55,644.98	33,417.82	34,584.46
30	98,073.42	54,031.40	34,288.34	33,481.90
31	101,162.42	55,377.00	38,590.20	32,580.38
32	104,989.18	56,181.88	37,888.62	33,713.16
33	103,941.70	58,548.78	39,418.48	36,599.44
34	108,149.78	61,838.24	35,312.92	36,913.76
35	105,219.46	59,461.08	35,984.74	35,576.70
36	102,712.58	60,835.18	35,968.10	38,847.28
37	101,229.36	61,595.28	37,689.68	40,739.76
38	100,442.46	63,382.78	39,278.20	40,746.16
39	98,375.98	59,359.36	38,822.56	40,753.58
40	96,388.54	63,178.06	38,081.30	42,360.64
41	94,930.22	58,023.16	35,284.44	40,432.76
42	95,243.16	58,457.44	37,143.58	38,886.98
43	101,202.68	59,304.66	35,905.90	40,965.00
44	102,921.32	62,714.92	34,338.64	38,622.94
45	100,519.58	64,290.42	36,823.18	34,821.32

Table A11. Means, Genetic Standard Deviations and Genetic Coefficients of Variation of Weekly Body Weight for Rhode Island Red Males

Age (wks.)	Mean Weight (gm)	Standard Deviation (gm)	Coefficient of Variation (%)
0	38.8	4.84	12.5
1	60.6	7.98	13.2
2	99.7	11.90	11.9
3	159.0	21.29	13.4
4	227.0	31.67	14.0
5	307.6	39.60	12.9
6	406.8	50.53	12.4
7	499.4	61.42	12.3
8	639.2	74.76	11.7
9	788.0	88.47	11.2
10	926.5	103.15	11.1
11	1027.8	106.77	10.4
12	1193.8	120.63	10.1
13	1394.5	141.62	10.2
14	1593.6	162.40	10.2
15	1780.8	187.11	10.5
16	1951.5	207.83	10.6
17	2081.8	222.12	10.7
18	2249.8	234.60	10.4
19	2384.2	247.58	10.4
20	2475.7	262.28	10.6
21	2602.0	272.48	10.5
22	2733.0	278.91	10.2
23	2831.9	292.95	10.3
24	2921.5	303.22	10.4
25	2993.7	304.05	10.2
26	3049.1	306.01	10.0
27	3080.6	311.17	10.1
28	3051.7	305.61	10.0
29	3084.7	305.79	9.9
30	3129.2	313.17	10.0
31	3150.4	318.06	10.1
32	3166.7	324.02	10.2
33	3179.3	322.40	10.1
34	3192.0	328.86	10.3
35	3185.5	324.38	10.2
36	3188.4	320.49	10.0
37	3175.8	318.16	10.0
38	3161.3	316.93	10.0
39	3158.3	313.65	9.9
40	3149.4	310.46	9.8
41	3133.3	308.11	9.8
42	3131.7	308.61	9.8
43	3139.4	318.12	10.1
44	3136.6	320.81	10.2
45	3118.3	317.05	10.2

Table A12. Means, Genetic Standard Deviations and Genetic Coefficients of Variation of Weekly Body Weights for Rhode Island Red Females

Age (wks.)	Mean Weight (gm)	Standard Deviation (gm)	Coefficient of Variation (%)
0	38.7	5.01	12.9
1	60.0	6.53	10.9
2	96.1	9.49	9.9
3	146.5	15.20	10.4
4	207.0	21.52	10.4
5	274.3	34.92	12.7
6	360.7	48.82	13.5
7	445.8	59.05	13.2
8	555.8	74.17	13.3
9	667.6	86.19	12.9
10	779.0	95.65	12.3
11	829.0	97.17	11.7
12	954.2	107.94	11.3
13	1096.4	121.49	11.1
14	1222.7	137.38	11.2
15	1327.3	143.31	10.8
16	1434.3	151.48	10.6
17	1519.3	155.98	10.3
18	1608.1	157.83	9.8
19	1678.0	165.21	9.8
20	1720.6	175.06	10.2
21	1772.8	186.10	10.5
22	1846.8	199.20	10.8
23	1935.1	219.60	11.3
24	2022.8	221.33	10.9
25	2113.0	224.54	10.6
26	2162.8	226.76	10.5
27	2203.5	229.07	10.4
28	2197.3	227.57	10.4
29	2207.1	235.89	10.7
30	2216.4	232.45	10.5
31	2231.3	235.32	10.5
32	2229.8	237.03	10.6
33	2237.9	241.97	10.8
34	2261.1	248.67	11.0
35	2255.9	243.85	10.8
36	2270.2	246.65	10.9
27	2280.0	248.18	10.9
38	2286.3	251.76	11.0
39	2276.6	243.64	10.7
40	2286.2	251.35	11.0
41	2266.2	240.88	10.6
42	2274.2	241.78	10.6
43	2316.3	243.52	10.5
44	2310.7	250.43	10.8
45	2320.0	253.56	10.9

Table A13. Means, Genetic Standard Deviations and Genetic Coefficients of Variation of Weekly Body Weights for White Leghorn Males

Age (wks.)	Mean Weight (gm)	Standard Deviation (gm)	Coefficient of Variation (%)
0	37.9	5.27	13.9
1	54.8	5.15	9.4
2	85.6	10.88	12.7
3	126.8	17.00	13.4
4	171.5	26.77	15.6
5	226.5	41.82	18.5
6	301.0	53.19	17.7
7	371.8	61.27	16.5
8	476.0	72.54	15.2
9	577.0	80.89	14.0
10	666.6	92.29	13.8
11	717.7	89.56	12.5
12	836.7	99.10	11.8
13	960.1	103.70	10.8
14	1078.5	112.38	10.4
15	1194.7	116.70	9.8
16	1309.5	122.65	9.4
17	1396.8	121.57	8.7
18	1526.8	133.50	8.7
19	1634.2	149.23	9.1
20	1704.3	156.24	9.2
21	1784.9	166.63	9.3
22	1861.0	174.42	9.4
23	1916.5	183.74	9.6
24	1947.1	188.42	9.7
25	1976.8	189.85	9.6
26	1994.0	195.93	9.8
27	2013.8	193.96	9.6
28	2025.9	185.69	9.2
29	2049.4	182.80	8.9
30	2076.2	185.17	8.9
31	2091.2	196.44	9.4
32	2100.4	194.65	9.3
33	2117.8	198.54	9.4
34	2116.0	187.92	8.9
35	2117.3	189.70	9.0
36	2128.7	189.65	8.9
37	2129.2	194.14	9.1
38	2126.6	198.19	9.3
39	2121.3	197.03	9.2
40	2117.1	195.14	9.2
41	2112.3	187.84	8.9
42	2112.0	192.73	9.1
43	2117.3	189.49	8.9
44	2113.6	185.31	8.8
45	2116.2	191.89	9.1

Table A14. Means, Genetic Standard Deviations and Genetic Coefficients of Variation of Weekly Body Weights for White Leghorn Females

Age (wks.)	Mean Weight (gm)	Standard Deviation (gm)	Coefficient of Variation (%)
0	38.1	4.85	12.7
1	56.0	6.54	11.7
2	86.5	14.85	17.2
3	125.0	23.18	18.5
4	164.5	32.99	20.0
5	211.8	46.15	21.8
6	269.3	55.92	20.8
7	333.9	65.96	19.8
8	411.4	79.65	19.4
9	501.5	90.04	18.0
10	575.7	101.58	17.6
11	596.9	101.95	17.1
12	686.6	98.75	14.4
13	785.2	98.40	12.5
14	856.7	99.16	11.6
15	936.1	104.94	11.2
16	1002.7	107.08	10.7
17	1044.9	106.59	10.2
18	1112.3	111.50	10.0
19	1164.9	112.61	9.7
20	1193.6	116.72	9.8
21	1220.4	118.94	9.7
22	1259.3	123.96	9.8
23	1297.8	138.24	10.6
24	1332.7	148.64	11.2
25	1380.8	162.48	11.8
26	1435.3	176.66	12.3
27	1499.2	183.44	12.2
28	1563.8	183.07	11.7
29	1606.5	185.97	11.6
30	1640.8	182.98	11.2
31	1652.2	180.50	10.9
32	1657.0	183.61	11.1
33	1671.9	191.31	11.4
34	1688.1	192.13	11.4
35	1691.3	188.62	11.2
36	1711.9	197.10	11.5
37	1724.1	201.84	11.7
38	1726.8	201.86	11.7
39	1724.2	201.88	11.7
40	1731.0	205.82	11.9
41	1719.6	201.08	11.7
42	1727.3	197.20	11.4
43	1740.4	202.40	11.6
44	1723.8	196.53	11.4
45	1713.0	186.60	10.9

Table A15. Heritability Estimates (h_S^2) and Standard Errors of Weekly Body Weights for Rhode Island Red and White Leghorn Males and Females

Age	RIR				WL			
	♂♂		♀♀		♂♂		♀♀	
Weeks	h^2	± s.e.	h^2	± s.e.	h^2	± s.e.	h^2	± s.e.
0	1.43	.75	1.34	.78	-.14	.96	-.28	.92
1	-.01	.58	-.71	.64	.55	.51	.43	.61
2	.34	.42	-.67	.46	.46	.48	.51	.54
3	.69	.39	-.51	.42	.36	.46	.28	.51
4	.70	.40	-.41	.39	.81	.45	.39	.49
5	.58	.39	-.31	.44	.94	.50	.50	.50
6	.52	.39	-.13	.44	.92	.49	.49	.48
7	.26	.40	-.20	.46	.91	.47	.53	.46
8	.22	.41	-.03	.44	.86	.46	.65	.47
9	.12	.43	.05	.45	.68	.47	.65	.47
10	.12	.44	.16	.44	.58	.50	.53	.50
11	.23	.41	.16	.43	.76	.46	.62	.51
12	.55	.39	.30	.44	.98	.49	.58	.49
13	.64	.42	.31	.47	.92	.49	.66	.46
14	.70	.44	.34	.50	.73	.51	.43	.49
15	.94	.45	.43	.50	.75	.49	.31	.51
16	.96	.47	.43	.51	.56	.49	.13	.53
17	1.07	.47	.48	.51	.81	.47	.04	.54
18	1.07	.47	.48	.51	.65	.48	.07	.55
19	1.10	.48	.50	.51	.56	.51	.11	.55
20	1.24	.49	.61	.51	.49	.52	.12	.56
21	1.15	.48	.66	.52	.53	.54	.10	.57
22	1.09	.48	.78	.49	.41	.55	.20	.57
23	1.02	.47	.80	.48	.40	.55	.29	.59
24	1.03	.47	.82	.46	.32	.57	.31	.59
25	1.04	.46	.80	.47	.49	.55	.32	.58
26	1.02	.47	.80	.49	.78	.54	.23	.58
27	.99	.48	.64	.51	.42	.55	.16	.58
28	.98	.48	.74	.51	.34	.55	.22	.56
29	.88	.48	.84	.51	.40	.54	.10	.57
30	.92	.49	.76	.51	.31	.55	-.14	.59
31	.94	.51	.69	.52	.33	.57	-.19	.59
32	1.00	.51	.76	.51	.40	.55	-.18	.61
33	.99	.51	.78	.52	.39	.57	-.22	.63
34	.96	.52	.77	.52	.59	.52	-.30	.63
35	.97	.52	.76	.50	.60	.52	-.36	.62
36	.92	.52	.88	.50	.55	.53	-.28	.63
37	.89	.52	.86	.50	.46	.54	-.44	.66
38	.93	.52	.77	.50	.48	.55	-.46	.66
39	.97	.52	.84	.47	.34	.57	-.38	.65
40	.97	.52	.70	.48	.32	.56	-.44	.67
41	.94	.51	.62	.47	.34	.54	-.36	.63
42	1.00	.52	.74	.46	.30	.56	-.34	.62
43	1.06	.52	.76	.46	.24	.55	-.45	.64
44	1.04	.52	.77	.46	.21	.55	-.46	.63
45	1.09	.53	.71	.46	.35	.55	-.27	.59

Table A16. Heritability Estimates (h_D^2) and Standard Errors of Weekly Body Weights for Rhode Island Red and White Leghorn Males and Females

Age	RIR				WL			
	♂♂		♀♀		♂♂		♀♀	
Weeks	h^2	± s.e.	h^2	± s.e.	h^2	± s.e.	h^2	± s.e.
0	1.51	.58	1.78	.65	3.35	1.28	3.20	1.18
1	1.58	.71	2.29	.91	.66	.58	1.47	.66
2	.64	.44	1.43	.67	.55	.56	1.10	.56
3	.25	.32	1.21	.61	.49	.56	1.10	.58
4	.34	.34	1.07	.56	.14	.43	.97	.54
5	.34	.35	1.23	.60	.29	.44	.95	.52
6	.39	.36	1.20	.58	.28	.44	.84	.50
7	.64	.44	1.38	.61	.16	.42	.71	.46
8	.70	.46	1.15	.56	.17	.43	.69	.44
9	.84	.51	1.13	.55	.35	.49	.71	.45
10	.90	.52	1.03	.52	.55	.55	.91	.51
11	.68	.46	1.01	.51	.25	.46	.92	.50
12	.39	.36	.96	.49	.20	.42	.85	.49
13	.44	.37	1.10	.52	.25	.44	.68	.44
14	.49	.37	1.22	.56	.52	.52	.94	.52
15	.40	.33	1.17	.54	.40	.49	1.08	.57
16	.44	.34	1.20	.55	.53	.54	1.25	.63
17	.36	.31	1.17	.53	.25	.45	1.33	.66
18	.35	.31	1.15	.53	.43	.51	1.40	.67
19	.38	.32	1.15	.53	.62	.56	1.36	.66
20	.30	.28	1.09	.50	.75	.60	1.40	.67
21	.36	.31	1.08	.50	.80	.61	1.44	.68
22	.38	.32	.87	.43	.96	.66	1.41	.67
23	.42	.33	.81	.42	.99	.67	1.47	.68
24	.40	.32	.70	.38	1.10	.70	1.47	.67
25	.35	.31	.74	.40	.89	.64	1.41	.66
26	.39	.32	.82	.42	.62	.54	1.45	.68
27	.48	.35	1.04	.49	.93	.65	1.46	.68
28	.49	.35	.98	.46	.96	.67	1.39	.66
29	.60	.39	.85	.42	.87	.64	1.48	.69
30	.62	.39	.97	.46	.98	.68	1.64	.75
31	.66	.40	1.05	.49	1.07	.69	1.67	.77
32	.65	.39	.98	.46	.96	.66	1.75	.79
33	.66	.40	1.01	.47	1.05	.68	1.85	.82
34	.73	.41	1.01	.47	.69	.58	1.88	.83
35	.70	.41	.93	.45	.68	.57	1.87	.83
36	.76	.42	.80	.41	.75	.60	1.87	.83
37	.75	.43	.82	.41	.89	.64	2.06	.89
38	.73	.42	.89	.44	.90	.64	2.05	.89
39	.69	.40	.72	.39	1.07	.69	1.99	.87
40	.69	.40	.89	.44	1.06	.69	2.10	.90
41	.69	.40	.90	.45	.95	.66	1.89	.84
42	.66	.39	.76	.41	1.04	.69	1.85	.82
43	.64	.38	.73	.40	1.06	.70	1.98	.87
44	.66	.39	.73	.40	1.04	.70	1.95	.86
45	.64	.38	.78	.42	.96	.67	1.71	.78

Table A17. Heritability Estimates (h^2_{S+D}) and Standard Errors of Weekly Body Weights for Rhode Island Red and White Leghorn Males and Females

Age	RIR				WL			
	♂♂		♀♀		♂♂		♀♀	
Weeks	h^2	± s.e.	h^2	± s.e.	h^2	± s.e.	h^2	± s.e.
0	1.47	.58	1.56	.62	1.60	1.10	1.46	1.02
1	.78	.60	.79	.76	.60	.51	.95	.59
2	.49	.39	.38	.56	.51	.49	.80	.51
3	.47	.30	.35	.50	.42	.49	.69	.51
4	.52	.32	.33	.47	.48	.40	.68	.48
5	.46	.32	.46	.50	.62	.42	.72	.47
6	.46	.33	.54	.49	.60	.42	.66	.45
7	.45	.39	.54	.51	.54	.40	.62	.42
8	.46	.40	.56	.48	.52	.40	.67	.41
9	.48	.44	.59	.47	.51	.44	.68	.42
10	.51	.45	.60	.45	.56	.49	.72	.46
11	.46	.40	.59	.44	.50	.42	.77	.46
12	.47	.33	.63	.43	.59	.40	.72	.45
13	.54	.34	.70	.46	.58	.41	.67	.41
14	.60	.35	.78	.49	.62	.47	.68	.47
15	.67	.34	.80	.48	.58	.45	.70	.51
16	.70	.34	.82	.48	.55	.48	.69	.55
17	.72	.33	.82	.47	.53	.42	.68	.57
18	.71	.33	.82	.47	.54	.46	.74	.59
19	.74	.34	.82	.47	.59	.50	.74	.58
20	.76	.32	.85	.46	.62	.53	.76	.59
21	.76	.33	.87	.46	.67	.54	.77	.60
22	.74	.34	.82	.41	.68	.58	.80	.59
23	.72	.34	.80	.40	.70	.58	.88	.60
24	.72	.34	.76	.37	.71	.61	.89	.60
25	.70	.33	.77	.38	.69	.56	.86	.58
26	.70	.34	.81	.40	.70	.49	.84	.59
27	.74	.35	.84	.45	.68	.57	.81	.60
28	.74	.36	.86	.43	.65	.58	.80	.58
29	.74	.38	.84	.41	.64	.56	.79	.60
30	.77	.38	.86	.43	.64	.59	.75	.65
31	.80	.39	.87	.45	.70	.61	.74	.66
32	.82	.39	.87	.44	.68	.58	.78	.68
33	.83	.39	.90	.44	.72	.60	.82	.70
34	.84	.40	.89	.44	.64	.51	.79	.71
35	.84	.40	.84	.42	.64	.51	.76	.71
36	.84	.41	.84	.40	.65	.53	.80	.71
37	.82	.41	.84	.40	.67	.56	.81	.76
38	.83	.40	.83	.42	.69	.56	.80	.76
39	.83	.40	.78	.38	.71	.60	.80	.74
40	.83	.40	.80	.41	.69	.60	.83	.77
41	.82	.40	.76	.41	.64	.58	.76	.72
42	.83	.39	.75	.38	.67	.60	.76	.70
43	.85	.39	.74	.38	.65	.61	.76	.74
44	.84	.39	.75	.38	.62	.61	.76	.73
45	.86	.39	.74	.39	.66	.58	.72	.67

Table A18. Sire Component of Variance Estimates of Weekly Body Weights for Rhode Island Red and White Leghorn Males and Females

Age (wks.)	RIR		WL	
	♂♂	♀♀	♂♂	♀♀
0	5.99	5.39	-0.60	-1.11
1	-0.05	-9.59	5.99	4.84
2	24.65	-40.00	27.04	34.91
3	165.78	-84.76	61.74	53.62
4	338.59	-144.97	304.28	157.34
5	493.84	-204.43	666.93	367.89
6	733.84	-144.51	1,086.48	573.27
7	543.70	-332.69	1,589.82	932.36
8	656.28	-82,41	2,193.27	1,531.57
9	486.10	146.35	2,163.02	1,941.13
10	630.50	615.41	2,197.04	1,909.49
11	1,442.63	648.84	2,999.12	2,091.68
12	4,266.42	1,418.49	4,065.88	1,964.28
13	5,937.93	1,631.91	4,227.49	2,391.00
14	7,764.62	2,068.69	3,686.84	1,538.65
15	12,239.32	2,781.09	4,459.31	1,221.17
16	14,851.67	3,009.12	3,891.72	539.16
17	18,503.64	3,559.38	5,666.14	163.19
18	20,721.23	3,634.38	5,371.32	293.93
19	22,678.98	4,134.64	5,303.46	471.84
20	27,641.75	5,519.08	4,806.66	518.89
21	28,205.99	6,551.28	5,550.89	481,38
22	28,785.22	9,374.98	4,563.81	974.45
23	30,408.30	11,998.81	4,899.12	1,567.04
24	33,133.75	13,198.36	4,029.62	1,925.84
25	34,462.20	13,094.81	6,377.52	2,474.01
26	33,801.14	12,690.17	10,699.22	2,165.15
27	32,705.66	10,029.68	5,860.61	1,691.90
28	31,252.96	11,144.17	4,546.75	2,286.98
29	27,927.84	13,810.89	5,329.19	1,087.86
30	29,150.54	11,845.70	4,126.19	-1,577.97
31	29,657.48	11,012.72	4,576.06	-2,094.55
32	31,797.67	12,277.37	5,533.12	-1,938.77
33	31,043.08	12,794.23	5,301.48	-2,485.06
34	30,789.75	13,407.76	8,107.46	-3,450.04
35	30,536.31	13,376.59	8,452.70	-4,288.54
36	28,168.85	15,935.77	7,608.67	-3,392.79
37	27,358.46	15,787.11	6,412.34	-5,526.85
38	28,125.39	14,684.33	6,856.61	-6,002.43
39	28,702.56	15,883.40	4,745.49	-4,840.19
40	28,194.36	13,907.85	4,405.08	-5,718.36
41	27,488.09	11,815.74	4,666.97	-4,706.38
42	28,808.75	14,362.83	4,159.47	-4,439.20
43	31,595.55	15,047.05	3,316.99	-6,057.05
44	31,445.41	16,064.78	2,859.80	-6,005.54
45	31,613.20	15,246.89	4,907.48	-3,320.94

Table A19. Dam Component of Variance Estimates of Weekly Body Weights for Rhode Island Red and White Leghorn Males and Females

Age (wks.)	RIR ♂♂	RIR ♀♀	WL ♂♂	WL ♀♀
0	6.32	7.15	13.96	12.88
1	20.17	30.92	7.29	16.53
2	46.12	85.02	32.10	75.38
3	60.93	200.37	82.74	214.93
4	163.04	376.64	53.96	386.90
5	290.42	814.24	207.37	696.95
6	542.60	1,336.29	328.22	990.18
7	1,342.64	2,075.98	287.36	1,242.71
8	2,138.43	2,833.02	437.90	1,640.53
9	3,427.78	3,568.29	1,108.84	2,122.14
10	4,689.47	3,959.03	2,062.12	3,249.42
11	4,257.68	4,072.52	1,011.07	3,105.30
12	3,008.95	4,407.02	844.77	2,911.76
13	4,090.48	5,747.61	1,149.17	2,450.45
14	5,422.43	7,367.35	2,628.08	3,377.73
15	5,265.14	7,487.38	2,350.34	4,285.04
16	6,744.18	8,464.82	3,629.36	5,195.16
17	6,165.92	8,605.93	1,724.05	5,517.65
18	6,797.20	8,820.88	3,540.29	5,922.60
19	7,968.91	9,512.78	5,831.33	5,868.25
20	6,752.62	9,804.40	7,398.70	6,293.32
21	8,917.26	10,765.97	8,332.20	6,592.37
22	10,109.61	10,464.56	10,648.19	6,708.21
23	12,500.79	12,124.26	11,980.65	7,988.62
24	12,836.27	11,294.63	13,721.57	9,121.03
25	11,762.26	12,113.34	11,643.67	10,726.05
26	13,021.35	13,019.85	8,494.43	13,438.56
27	15,706.97	16,206.44	12,949.65	15,133.52
28	15,445.40	14,750.92	12,693.01	14,470.48
29	18,826.89	14,011.60	11,379.72	16,204.37
30	19,886.17	15,170.00	13,017.98	18,318.92
31	20,923.73	16,675.78	14,716.04	18,384.74
32	20,696.92	15,813.57	13,411.19	18,795.35
33	20,927.77	16,480.16	14,407.76	20,784.78
34	23,285.14	17,511.36	9,549.00	21,906.92
35	22,073.42	16,353.95	9,539.67	22,076.89
36	23,187.44	14,481.82	10,375.38	22,816.43
37	23,256.22	15,010.53	12,432.50	25,896.73
38	22,095.84	17,007.06	12,782.49	26,375.61
39	20,485.43	13,796.28	14,665.79	25,216.98
40	19,999.91	17,681.18	14,635.57	26,898.68
41	19,977.02	17,195.84	12,975.25	24,922.76
42	18,812.83	14,865.89	14,412.32	23,882.69
43	19,005.79	14,605.28	14,635.96	26,539.55
44	20,015.25	15,292.68	14,309.52	25,317.01
45	18,646.59	16,898.32	13,504.11	20,731.60

Table A20. Correlations Between Consecutive Weekly Body Weights for Rhode Island Red and White Leghorn Males and Females

Weeks	RIR		WL	
	♂♂	♀♀	♂♂	♀♀
0	.5612	.5179	.3880	.4734
1	.7999	.8052	.7775	.8231
2	.9343	.9123	.9037	.9293
3	.9578	.9410	.9276	.9577
4	.9623	.9513	.9568	.9695
5	.9684	.9774	.9675	.9790
6	.9718	.9808	.9745	.9799
7	.9833	.9842	.9754	.9849
8	.9839	.9874	.9771	.9883
9	.9883	.9856	.9830	.9815
10	.9729	.9753	.9729	.9816
11	.9765	.9848	.9711	.9796
12	.9866	.9836	.9696	.9776
13	.9886	.9810	.9553	.9704
14	.9775	.9803	.9741	.9756
15	.9832	.9830	.9762	.9727
16	.9857	.9885	.9795	.9798
17	.9884	.9909	.9797	.9801
18	.9908	.9940	.9871	.9863
19	.9832	.9906	.9890	.9871
20	.9856	.9900	.9878	.9882
21	.9905	.9835	.9904	.9906
22	.9915	.9832	.9923	.9863
23	.9938	.9805	.9924	.9878
24	.9932	.9736	.9899	.9821
25	.9947	.9651	.9786	.9800
26	.9936	.9618	.9798	.9707
27	.9927	.9611	.9888	.9599
28	.9890	.9703	.9924	.9587
29	.9945	.9745	.9929	.9716
30	.9968	.9845	.9960	.9793
31	.9970	.9851	.9959	.9835
32	.9952	.9837	.9960	.9795
33	.9953	.9885	.9870	.9839
34	.9955	.9914	.9955	.9907
35	.9968	.9913	.9962	.9898
36	.9957	.9933	.9954	.9875
37	.9964	.9895	.9942	.9896
38	.9958	.9872	.9950	.9880
39	.9971	.9874	.9954	.9908
40	.9943	.9853	.9968	.9844
41	.9970	.9850	.9948	.9884
42	.9968	.9893	.9962	.9855
43	.9962	.9872	.9964	.9855
44	.9961	.9865	.9945	.9790

Table A21. Correlations Between Initial and Successive Body Weights for Rhode Island Red and White Leghorn Males and Females

Weeks	RIR		WL	
	♂♂	♀♀	♂♂	♀♀
0	1.0000	1.0000	1.0000	1.0000
1	.5612	.5179	.3880	.4734
2	.2586	.2197	.2005	.2852
3	.1745	.1614	.2118	.2347
4	.1151	.1255	.2812	.2193
5	.1097	.1003	.2968	.1979
6	.1020	.0753	.2740	.1953
7	.1039	.0657	.2396	.1897
8	.0926	.0495	.2336	.2196
9	.0946	.0334	.2432	.2221
10	.0970	.0387	.2650	.2322
11	.1080	.0512	.2737	.2457
12	.1094	.0898	.3142	.2506
13	.1306	.1086	.3207	.2588
14	.1429	.1145	.3458	.2802
15	.1366	.1409	.3373	.2822
16	.1475	.1685	.3371	.2652
17	.1574	.1861	.3226	.2609
18	.1643	.1901	.3205	.2821
19	.1619	.1901	.3411	.2962
20	.1449	.1852	.3585	.2863
21	.1678	.1902	.3666	.2989
22	.1763	.1762	.3555	.3002
23	.1504	.1649	.3430	.2996
24	.1493	.1811	.3414	.2992
25	.1495	.1834	.3351	.2980
26	.1373	.1863	.3028	.2877
27	.1448	.1969	.3049	.2731
28	.1477	.2051	.3142	.2580
29	.1418	.2056	.3110	.3074
30	.1359	.2151	.3177	.3397
31	.1412	.2068	.3114	.3416
32	.1417	.2109	.3172	.3431
33	.1392	.1986	.3187	.3517
34	.1364	.1995	.3082	.3683
35	.1271	.1911	.3030	.3647
36	.1221	.1846	.3160	.3560
37	.1219	.1853	.3184	.3537
38	.1215	.1937	.3152	.3518
39	.1181	.1701	.3230	.3487
40	.1148	.1878	.3197	.3196
41	.1093	.1719	.3140	.3157
42	.1178	.1799	.3245	.3098
43	.1184	.1667	.3224	.3081
44	.1202	.1734	.3199	.3086
45	.1138	.1607	.3278	.3001

Table A22. Correlations Between Final and Preceding Body Weights for Rhode Island Red and White Leghorn Males and Females

Weeks	RIR		WL	
	♂♂	♀♀	♂♂	♀♀
0	.1138	.1607	.3278	.3001
1	.3056	.2256	.3629	.3206
2	.3187	.2597	.2646	.2934
3	.2885	.2891	.2340	.2976
4	.2946	.2812	.2302	.3243
5	.2865	.3128	.1871	.3250
6	.3423	.3252	.1969	.3343
7	.3829	.3582	.2049	.3544
8	.4171	.3782	.2772	.3676
9	.4413	.4008	.3076	.3883
10	.4776	.4330	.3388	.4207
11	.5264	.4665	.3843	.4705
12	.5863	.5094	.4543	.5141
13	.6278	.5690	.5146	.5583
14	.6716	.6135	.5905	.6097
15	.7002	.6453	.6364	.6510
16	.7141	.6902	.6949	.6804
17	.7544	.7166	.7335	.7063
18	.7718	.7443	.7750	.7649
19	.7919	.7556	.8201	.7986
20	.8246	.7542	.8480	.8192
21	.8358	.7473	.8664	.8232
22	.8426	.7325	.8818	.8336
23	.8579	.7061	.8968	.8145
24	.8721	.7117	.9110	.7909
25	.8880	.7286	.9239	.7566
26	.8990	.7515	.9211	.7302
27	.9133	.7629	.9392	.7194
28	.9259	.7874	.9503	.7554
29	.9315	.8171	.9518	.8013
30	.9412	.8473	.9604	.8401
31	.9496	.8588	.9660	.8630
32	.9533	.8812	.9671	.8778
33	.9606	.9045	.9693	.8993
34	.9664	.9180	.9687	.9161
35	.9716	.9256	.9675	.9205
36	.9746	.9326	.9731	.9260
37	.9757	.9385	.9789	.9258
38	.9788	.9475	.9815	.9328
39	.9836	.9562	.9843	.9350
40	.9863	.9684	.9879	.9412
41	.9881	.9724	.9887	.9494
42	.9921	.9690	.9919	.9517
43	.9937	.9741	.9925	.9557
44	.9961	.9865	.9945	.9790
45	1.0000	1.0000	1.0000	1.0000

Table A23. Means and Standard Deviations of Weekly Gains in Body Weight for Rhode Island Red Males

Gain Period	Age Interval (wks.)	Mean Gain (gm)	Standard Deviation (gm)
0	0-1	21.8	5.89
1	1-2	39.1	11.98
2	2-3	59.4	16.22
3	3-4	67.9	16.65
4	4-5	80.6	19.83
5	5-6	99.2	23.57
6	6-7	92.7	25.70
7	7-8	139.8	26.12
8	8-9	148.8	27.28
9	9-10	138.5	26.49
10	10-11	101.3	37.92
11	11-12	166.0	39.96
12	12-13	200.7	34.03
13	13-14	199.1	34.88
14	14-15	187.1	49.84
15	15-16	170.7	47.60
16	16-17	130.3	45.33
17	17-18	168.0	43.83
18	18-19	134.4	39.20
19	19-20	91.5	54.58
20	20-21	126.2	53.42
21	21-22	131.0	45.46
22	22-23	98.9	47.62
23	23-24	89.6	41.22
24	24-25	72.2	42.24
25	25-26	55.4	37.28
26	26-27	31.5	40.73
27	27-28	-28.8	43.73
28	28-29	33.0	52.47
29	29-30	44.5	37.08
30	30-31	21.2	28.21
31	31-32	16.4	27.46
32	32-33	12.6	34.80
33	33-34	12.6	34.64
34	34-35	-6.4	33.69
35	35-36	2.9	28.50
36	36-37	-12.6	32.27
37	37-38	-14.5	29.53
38	38-39	-3.0	31.76
39	39-40	-8.9	26.16
40	40-41	-16.1	36.30
41	41-42	-1.6	26.41
42	42-43	7.7	27.83
43	43-44	-2.7	30.08
44	44-45	-18.3	31.10

Table A24. Means and Standard Deviations of Weekly Gains in Body Weight for Rhode Island Red Females

Gain Period	Age Interval (wks.)	Mean Gain (gm)	Standard Deviation (gm)
0	0-1	21.3	6.28
1	1-2	36.1	10.46
2	2-3	50.4	13.22
3	3-4	60.5	15.91
4	4-5	67.3	19.46
5	5-6	86.4	19.79
6	6-7	85.0	19.74
7	7-8	110.0	24.38
8	8-9	111.9	21.28
9	9-10	111.4	23.13
10	10-11	50.0	27.96
11	11-12	125.2	24.35
12	12-13	142.2	26.70
13	13-14	126.3	31.05
14	14-15	104.6	31.55
15	15-16	107.2	31.08
16	16-17	84.8	25.88
17	17-18	88.8	23.45
18	18-19	69.9	20.58
19	19-20	42.7	26.54
20	20-21	52.2	29.15
21	21-22	74.0	42.57
22	22-23	88.3	49.32
23	23-24	87.7	49.97
24	24-25	90.2	58.21
25	25-26	49.8	66.69
26	26-27	40.7	68.88
27	27-28	-6.3	68.79
28	28-29	9.8	61.71
29	29-30	9.3	57.17
30	30-31	14.9	43.98
31	31-32	-1.5	43.52
32	32-33	8.1	45.77
33	33-34	23.2	39.86
34	34-35	-5.2	34.48
35	35-36	14.3	35.06
36	36-37	9.8	31.29
37	37-38	6.3	39.86
38	38-39	-9.7	43.97
39	39-40	9.6	44.43
40	40-41	-20.0	47.84
41	41-42	8.0	47.94
42	42-43	42.1	40.95
43	43-44	-5.7	45.80
44	44-45	9.4	47.95

Table A25. Means and Standard Deviations of Weekly Gain in Body Weight for White Leghorn Males

Gain Period	Age Interval (wks.)	Mean Gain (gm)	Standard Deviation (gm)
0	0-1	16.9	6.26
1	1-2	30.7	10.89
2	2-3	41.2	13.90
3	3-4	44.6	17.39
4	4-5	55.1	19.49
5	5-6	74.4	21.69
6	6-7	70.8	22.67
7	7-8	104.2	26.66
8	8-9	101.0	25.74
9	9-10	89.6	23.67
10	10-11	51.2	29.02
11	11-12	119.0	30.66
12	12-13	123.4	33.12
13	13-14	118.4	41.90
14	14-15	116.2	35.41
15	15-16	114.8	36.77
16	16-17	87.4	33.59
17	17-18	130.0	38.11
18	18-19	107.4	32.20
19	19-20	70.0	29.33
20	20-21	80.6	31.86
21	21-22	76.1	29.46
22	22-23	55.5	28.16
23	23-24	30.5	27.40
24	24-25	29.8	32.27
25	25-26	17.2	47.90
26	26-27	19.7	47.04
27	27-28	12.1	35.16
28	28-29	23.6	28.19
29	29-30	26.7	27.39
30	30-31	15.1	20.99
31	31-32	9.1	21.49
32	32-33	17.5	21.07
33	33-34	-1.8	37.63
34	34-35	1.2	22.37
35	35-36	11.4	20.45
36	36-37	0.5	22.54
37	37-38	-2.6	25.52
38	38-39	-5.3	23.89
39	39-40	-4.2	22.43
40	40-41	-4.8	18.79
41	41-42	-0.4	23.84
42	42-43	5.3	20.43
43	43-44	-3.8	19.82
44	44-45	2.7	24.85

Table A26. Means and Standard Deviations of Weekly Gains in Body Weight for White Leghorn Females

Gain Period	Age Interval (wks.)	Mean Gain (gm)	Standard Deviation (gm)
0	0-1	17.9	5.94
1	1-2	30.5	11.59
2	2-3	38.5	13.91
3	3-4	39.5	15.41
4	4-5	47.4	18.20
5	5-6	57.4	19.02
6	6-7	64.6	21.23
7	7-8	77.5	20.78
8	8-9	90.1	19.61
9	9-10	74.2	24.28
10	10-11	21.1	22.78
11	11-12	89.7	23.43
12	12-13	98.6	25.24
13	13-14	71.6	29.15
14	14-15	79.4	27.71
15	15-16	66.6	29.83
16	16-17	42.2	25.82
17	17-18	67.4	25.78
18	18-19	52.6	21.64
19	19-20	28.7	21.37
20	20-21	26.8	20.62
21	21-22	38.9	18.84
22	22-23	38.5	25.29
23	23-24	34.9	25.78
24	24-25	48.1	35.43
25	25-26	54.5	40.83
26	26-27	63.9	49.08
27	27-28	64.5	57.59
28	28-29	42.7	59.44
29	29-30	34.3	50.04
30	30-31	11.4	42.82
31	31-32	4.8	37.86
32	32-33	14.9	42.57
33	33-34	16.2	38.52
34	34-35	3.2	29.46
35	35-36	20.6	31.38
36	36-37	12.2	35.27
37	37-38	2.7	32.55
38	38-39	-2.5	34.95
39	39-40	6.8	30.54
40	40-41	-11.3	40.26
41	41-42	7.6	34.83
42	42-43	13.1	39.20
43	43-44	-16.5	39.14
44	44-45	-10.8	46.45

Table A27. Sire Component of Variance Estimates of Gains in Weekly Body Weight for Rhode Island Red and White Leghorn Males and Females

Gain Period	RIR		WL	
	♂♂	♀♀	♂♂	♀♀
0	-4.46	-5.29	2.08	5.54
1	17.67	-3.69	17.30	11.31
2	54.19	-13.19	17.64	2.20
3	29.00	8.77	81.76	23.19
4	23.26	35.76	82.28	46.57
5	14.30	28.33	39.02	12.11
6	-6.23	-24.06	61.42	52.18
7	-11.37	63.70	32.13	97.24
8	-33.54	57.15	-117.85	38.70
9	31.26	78.74	5.26	-73.51
10	179.14	84.35	28.60	-115.39
11	411.26	119.02	204.10	49.67
12	274.47	67.40	-91.10	30.25
13	151.95	31.62	119.98	34.86
14	515.34	42.49	11.10	33.97
15	99.56	69.56	-121.76	62.77
16	567.46	111.42	-234.30	-10.60
17	115.49	74.13	-312.65	31.15
18	-37.41	44.87	2.94	44.37
19	487.38	105.78	31.47	35.95
20	443.49	86.45	140.88	55.37
21	114.14	179.38	10.60	33.05
22	-541.07	232.44	107.56	66.05
23	193.55	70.61	59.38	25.68
24	277.02	-3.04	8.25	140.58
25	39.88	73.63	-92.82	53.14
26	162.43	295.74	-562.24	355.11
27	-66.80	94.90	204.13	319.31
28	-170.43	249.17	12.44	495.98
29	-96.54	-192.70	68.93	108.90
30	102.90	-121.80	27.95	102.16
31	-38.72	61.45	16.56	-6.55
32	99.38	-28.84	-28.94	234.05
33	35.50	70.51	-569.31	207.47
34	67.86	-117.47	80.67	70.71
35	-93.44	56.38	25.28	60.70
36	-90.84	-117.99	1.49	83.80
37	30.12	-109.16	48.47	23.30
38	110.69	-77.47	-40.92	-35.00
39	3.96	-15.11	-90.59	-41.63
40	-14.52	270.49	-17.54	41.17
41	43.16	-371.16	28.22	-4.07
42	98.05	27.32	-16.54	62.26
43	105.21	79.24	17.53	114.16
44	-179.56	15.71	86.32	-168.34

Table A28. Dam Component of Variance Estimates of Gains in Weekly Body Weight for Rhode Island Red and White Leghorn Males and Females

Gain Period	RIR		WL	
	♂♂	♀♀	♂♂	♀♀
0	9.73	11.63	2.94	7.50
1	13.63	18.80	1.71	29.55
2	1.65	37.01	1.24	35.23
3	54.03	29.54	-14.50	33.64
4	35.57	97.35	35.90	48.81
5	56.93	75.16	18.10	34.79
6	121.83	99.44	-18.93	23.74
7	149.83	81.34	10.11	2.36
8	163.27	34.22	225.75	31.71
9	79.20	39.72	142.64	175.68
10	-70.04	58.24	-21.69	230.43
11	-104.98	25.57	-52.19	-24.30
12	86.56	164.68	281.01	-42.50
13	150.40	158.23	-16.11	28.56
14	-62.64	37.21	95.64	-2.14
15	206.32	32.66	188.02	13.62
16	-97.33	16.03	302.53	19.08
17	36.27	44.75	500.40	24.05
18	221.22	16.81	87.73	-16.39
19	687.72	71.12	57.68	26.27
20	-57.65	126.55	51.01	5.04
21	-26.84	33.60	107.87	12.65
22	857.47	149.77	10.84	46.04
23	-79.88	36.37	28.13	79.55
24	71.42	253.74	-90.22	94.05
25	102.83	400.33	985.17	235.58
26	29.92	173.27	1,297.83	-209.05
27	330.66	162.50	-183.83	69.73
28	207.92	102.07	-113.82	-40.84
29	175.67	426.93	-31.65	430.63
30	-27.42	258.19	87.08	-40.75
31	116.66	-155.28	-37.46	1.01
32	5.39	72.44	15.64	-117.41
33	17.41	-34.47	887.17	-195.22
34	-25.54	128.36	-64.18	-23.97
35	205.12	-72.99	-3.62	-29.22
36	111.24	207.40	53.44	-148.90
37	-19.12	199.70	-47.09	-136.37
38	-28.58	-7.07	44.06	-34.53
39	-78.09	130.47	100.01	71.74
40	165.85	46.17	26.12	-165.54
41	-75.61	437.46	10.04	6.44
42	-99.32	-13.04	-11.03	-93.06
43	-87.16	-99.76	-34.12	-168.61
44	217.12	-148.84	24.99	38.78

Table A29. Estimates of Full Sib Group Variances (Sire Plus Dam Components) of Gains in Weekly Body Weight for Rhode Island Red and White Leghorn Males and Females

Gain Period	RIR		WL	
	♂♂	♀♀	♂♂	♀♀
0	5.27	6.34	5.02	13.04
1	31.30	15.11	19.01	40.86
2	55.84	23.82	18.88	37.43
3	83.03	38.31	67.26	56.83
4	58.83	133.11	118.18	95.38
5	71.23	103.49	57.12	46.90
6	115.60	75.38	42.49	75.92
7	138.46	145.04	42.24	99.60
8	129.73	91.37	107.90	70.41
9	110.46	118.46	147.90	102.17
10	109.10	142.59	6.91	115.04
11	306.28	144.59	151.91	25.37
12	361.03	232.08	189.91	-12.25
13	302.35	189.85	103.87	63.42
14	452.70	79.70	106.74	31.83
15	305.88	102.22	66.26	76.39
16	470.13	127.45	68.23	8.48
17	151.76	118.88	187.75	55.20
18	183.81	61.68	90.67	27.98
19	1,175.10	176.90	89.15	62.22
20	385.84	213.00	191.89	60.41
21	87.30	212.98	118.47	45.70
22	316.40	382.21	118.40	112.09
23	113.67	106.98	87.51	105.23
24	348.44	250.70	-81.97	234.63
25	142.71	473.96	892.35	288.72
26	192.35	469.01	735.59	146.06
27	263.86	257.40	20.30	389.04
28	37.49	351.24	101.38	455.14
29	79.13	234.23	37.28	539.53
30	75.48	136.39	115.03	61.41
31	77.94	-93.83	-20.90	-5.54
32	104.77	43.60	-13.30	116.64
33	52.91	36.04	317.86	12.25
34	42.32	10.89	16.49	46.74
35	111.68	16.61	21.66	31.48
36	20.84	89.41	54.93	65.10
37	11.00	90.54	1.38	113.07
38	82.11	84.54	3.14	-69.53
39	-74.13	115.36	9.42	30.11
40	151.33	316.66	8.58	124.37
41	-32.45	66.30	38.26	2.37
42	-1.27	14.28	-27.84	-30.80
43	18.05	20.52	-16.59	54.45
44	37.56	-133.13	111.31	-129.56

Table A30. Heritability Estimates (h_S^2) and Standard Errors of Gains in Weekly Body Weight for Rhode Island Red and White Leghorn Males and Females

Gain Period	RIR				WL			
	♂♂		♀♀		♂♂		♀♀	
	h^2	± s.e.	h^2	± s.e.	h^2	± s.e.	h^2	± s.e.
0	-.51	.44	-.54	.41	.21	.41	.62	.50
1	.49	.38	-.13	.33	.58	.40	.33	.47
2	.82	.36	-.30	.35	.36	.37	.04	.40
3	.42	.45	.14	.31	1.07	.43	.39	.40
4	.24	.34	.37	.46	.86	.50	.56	.43
5	.10	.34	.29	.40	.33	.39	.13	.34
6	-.04	.39	-.25	.39	.48	.35	.46	.34
7	-.07	.42	.42	.37	.18	.36	.89	.37
8	-.18	.41	.50	.33	-.71	.55	.40	.36
9	.18	.36	.58	.34	.04	.53	-.50	.47
10	.50	.27	.43	.32	.14	.32	-.89	.58
11	1.02	.35	.80	.35	.86	.39	.36	.24
12	.94	.43	.38	.44	-.33	.50	.19	.20
13	.50	.40	.13	.35	.27	.35	.16	.29
14	.82	.34	.17	.25	.04	.39	.18	.26
15	.18	.34	.29	.26	-.36	.42	.28	.28
16	1.09	.38	.66	.31	-.83	.50	-.06	.26
17	.24	.28	.54	.34	-.86	.55	.19	.29
18	-.10	.36	.42	.28	.01	.40	.38	.25
19	.65	.51	.60	.36	.15	.40	.31	.32
20	.62	.31	.40	.38	.55	.43	.52	.31
21	.22	.25	.39	.26	.05	.43	.37	.31
22	-.96	.51	.38	.30	.54	.40	.41	.35
23	.45	.26	.11	.22	.32	.39	.15	.36
24	.62	.36	-.01	.26	.03	.27	.44	.36
25	.11	.32	.07	.28	-.16	.64	.13	.38
26	.39	.30	.25	.26	-1.01	.72	.59	.24
27	-.14	.38	.08	.23	.66	.29	.38	.30
28	-.25	.29	.26	.25	.06	.23	.56	.30
29	-.28	.33	-.24	.29	.37	.34	.17	.41
30	.52	.28	-.25	.29	.25	.50	.22	.24
31	-.20	.36	.13	.14	.14	.28	-.02	.24
32	.33	.28	-.06	.22	-.26	.35	.51	.25
33	.12	.26	.18	.20	-1.61	.74	.56	.20
34	.24	.25	-.40	.26	.64	.31	.32	.25
35	-.46	.42	.18	.16	.24	.35	.25	.24
36	-.35	.31	-.48	.34	.01	.41	.27	.17
37	.14	.24	-.27	.28	.30	.30	.09	.14
38	.44	.28	-.16	.18	-.29	.38	-.11	.21
39	.02	.15	-.03	.25	-.72	.45	-.18	.30
40	-.04	.34	.47	.28	-.20	.38	.10	.16
41	.25	.18	-.65	.32	.20	.36	-.01	.25
42	.50	.21	.06	.19	-.16	.30	.16	.20
43	.46	.22	.15	.17	.18	.28	.30	.18
44	-.74	.39	.03	.14	.56	.42	-.31	.24

Table A31. Heritability Estimates (h_D^2) and Standard Errors of Gains in Weekly Body Weight for Rhode Island Red and White Leghorn Males and Females

Gain Period	RIR				WL			
	♂♂		♀♀		♂♂		♀♀	
	h^2	± s.e.	h^2	± s.e.	h^2	± s.e.	h^2	± s.e.
0	1.12	.63	1.18	.60	.30	.54	.84	.48
1	.38	.36	.68	.44	.06	.44	.87	.52
2	.02	.25	.85	.49	.02	.46	.72	.50
3	.77	.47	.46	.36	-.19	.33	.56	.43
4	.36	.38	1.02	.50	.37	.47	.58	.42
5	.41	.40	.76	.44	.15	.49	.38	.40
6	.74	.49	1.02	.54	-.15	.41	.21	.33
7	.88	.53	.54	.37	.06	.49	.02	.25
8	.88	.54	.30	.30	1.36	.89	.33	.37
9	.45	.40	.29	.29	1.01	.72	1.19	.66
10	-.19	.22	.30	.30	-.10	.46	1.78	.85
11	-.26	.17	.17	.24	-.22	.35	-.18	.24
12	.30	.31	.92	.47	1.02	.76	-.27	.24
13	.49	.39	.65	.42	-.04	.46	.13	.34
14	-.10	.22	.15	.28	.30	.56	-.01	.30
15	.36	.38	.13	.27	.56	.67	.06	.31
16	-.19	.18	.10	.23	1.07	.84	.11	.35
17	.08	.30	.32	.30	1.38	.91	.14	.34
18	.57	.46	.16	.26	.34	.57	-.14	.25
19	.91	.48	.40	.32	.27	.54	.23	.35
20	-.08	.24	.59	.38	.20	.48	.05	.29
21	-.05	.28	.07	.24	.50	.60	.14	.32
22	1.52	.76	.24	.29	.05	.45	.29	.36
23	-.19	.23	.06	.26	.15	.49	.48	.43
24	.16	.30	.30	.33	-.35	.43	.30	.36
25	.30	.37	.36	.34	1.70	.90	.56	.45
26	.07	.29	.14	.27	2.34	1.15	-.34	.19
27	.69	.49	.14	.28	-.59	.31	.08	.31
28	.30	.40	.11	.26	-.57	.38	-.05	.26
29	.51	.45	.52	.40	-.17	.42	.68	.48
30	-.14	.23	.53	.41	.78	.64	-.09	.28
31	.62	.47	-.33	.16	-.32	.42	.00	.32
32	.02	.28	.14	.29	.14	.56	-.26	.21
33	.06	.31	-.09	.22	2.51	1.26	-.52	.15
34	-.09	.27	.43	.39	-.51	.32	-.11	.26
35	1.01	.59	-.24	.18	-.03	.46	-.12	.27
36	.43	.44	.85	.51	.42	.59	-.48	.18
37	-.09	.27	.50	.40	-.29	.41	-.52	.19
38	-.11	.24	-.01	.26	.31	.60	-.11	.30
39	-.46	.20	.26	.32	.80	.76	.31	.41
40	.50	.43	.08	.24	.30	.59	-.41	.21
41	-.43	.19	.76	.49	.07	.49	.02	.32
42	-.51	.15	-.03	.24	-.11	.50	-.24	.25
43	-.38	.18	-.19	.19	-.35	.41	-.44	.19
44	.90	.59	-.26	.18	.16	.47	.07	.36

Table A32. Heritability Estimates (h^2_{S+D}) and Standard Errors of Gains in Weekly Body Weight for Rhode Island Red and White Leghorn Males and Females

Gain Period	RIR				WL			
	♂♂		♀♀		♂♂		♀♀	
	h^2	± s.e.	h^2	± s.e.	h^2	± s.e.	h^2	± s.e.
0	.30	.52	.32	.50	.26	.46	.73	.45
1	.43	.33	.28	.37	.32	.39	.60	.46
2	.42	.26	.27	.41	.20	.39	.39	.43
3	.59	.42	.30	.32	.44	.32	.48	.39
4	.30	.38	.70	.44	.62	.44	.57	.39
5	.26	.34	.52	.38	.24	.42	.26	.35
6	.35	.42	.39	.45	.16	.35	.34	.30
7	.40	.45	.48	.33	.12	.41	.46	.26
8	.35	.45	.40	.28	.32	.74	.36	.33
9	.31	.35	.44	.28	.52	.61	.35	.56
10	.15	.21	.36	.28	.02	.38	.44	.71
11	.38	.21	.48	.26	.32	.32	.09	.22
12	.62	.32	.65	.42	.35	.64	-.04	.20
13	.49	.36	.39	.36	.12	.39	.15	.29
14	.36	.23	.16	.24	.17	.47	.08	.26
15	.27	.33	.21	.24	.10	.55	.17	.27
16	.45	.23	.38	.24	.12	.69	.02	.30
17	.16	.27	.43	.28	.26	.76	.17	.30
18	.24	.38	.29	.24	.18	.48	.12	.23
19	.78	.45	.50	.30	.21	.46	.27	.31
20	.27	.23	.50	.34	.38	.42	.28	.27
21	.08	.24	.23	.23	.27	.51	.26	.29
22	.28	.63	.31	.26	.30	.39	.35	.32
23	.13	.21	.09	.22	.23	.42	.32	.37
24	.39	.28	.15	.28	-.16	.34	.37	.32
25	.20	.32	.21	.29	.77	.77	.34	.39
26	.23	.26	.20	.24	.66	.96	.12	.18
27	.28	.41	.11	.24	.03	.26	.23	.28
28	.03	.33	.18	.23	-.26	.30	.26	.25
29	.12	.38	.14	.34	.10	.36	.43	.42
30	.19	.22	.14	.34	.52	.55	.07	.24
31	.21	.40	-.10	.13	-.09	.34	-.01	.27
32	.17	.25	.04	.24	-.06	.46	.13	.20
33	.09	.26	.04	.19	.45	1.05	.02	.15
34	.07	.23	.02	.32	.07	.28	.11	.24
35	.28	.49	-.03	.15	.10	.39	.06	.23
36	.04	.36	.18	.42	.22	.50	-.10	.15
37	.02	.23	.11	.33	.00	.34	-.21	.15
38	.16	.22	-.09	.21	.01	.50	-.11	.25
39	-.22	.16	.12	.27	.04	.63	.06	.34
40	.23	.37	.28	.23	.05	.49	-.15	.17
41	-.09	.16	.06	.41	.13	.41	.00	.27
42	-.01	.15	.02	.20	-.13	.40	-.04	.21
43	.04	.17	-.02	.16	-.08	.33	-.07	.16
44	.08	.48	-.12	.15	.36	.41	-.12	.30

Table A33. Estimates of Full Sib Group Standard Deviations of Gains in Weekly Body Weight for Rhode Island Red and White Leghorn Males and Females

Gain Period	RIR		WL	
	♂♂	♀♀	♂♂	♀♀
0	2.29	2.52	2.24	3.61
1	5.59	3.89	4.36	6.39
2	7.47	4.88	4.34	6.12
3	9.11	6.19	8.20	7.54
4	7.67	11.54	10.87	9.77
5	8.44	10.17	7.56	6.85
6	10.75	8.68	6.52	8.71
7	11.77	12.04	6.50	9.98
8	11.39	9.56	10.39	8.39
9	10.51	10.88	12.16	10.11
10	10.44	11.94	2.63	10.73
11	17.50	12.02	12.32	5.04
12	19.00	15.23	13.78	0.00
13	17.39	13.78	10.19	7.96
14	21.28	8.93	10.33	5.64
15	17.49	10.11	8.14	8.74
16	21.68	11.29	8.26	2.91
17	12.32	10.90	13.70	7.43
18	13.56	7.85	9.52	5.29
19	34.28	13.30	9.44	7.89
20	19.64	14.59	13.85	7.77
21	9.34	14.59	10.88	6.76
22	17.79	19.55	10.88	10.59
23	10.66	10.34	9.35	10.26
24	18.66	15.83	0.00	15.32
25	11.95	21.77	29.87	16.99
26	13.87	21.66	27.12	12.08
27	16.24	16.04	4.50	19.72
28	6.12	18.74	10.07	21.33
29	8.90	15.30	6.10	23.23
30	8.69	11.68	10.73	7.84
31	8.83	0.00	0.00	0.00
32	10.24	6.60	0.00	10.80
33	7.27	6.00	17.83	3.50
34	6.50	3.30	4.06	6.84
35	10.57	4.08	4.65	5.61
36	4.57	9.46	7.41	8.07
37	3.32	9.52	1.17	10.63
38	9.06	9.19	1.77	0.00
39	0.00	10.74	3.07	5.49
40	12.30	17.79	2.93	11.15
41	0.00	8.14	6.18	1.54
42	0.00	3.78	0.00	0.00
43	4.25	4.53	0.00	7.38
44	6.13	0.00	10.55	0.00

Table A34. Correlations Between Consecutive Gains in Weekly Body Weight for Rhode Island Red and White Leghorn Males and Females

Weeks (t-1)	RIR		WL	
	♂♂	♀♀	♂♂	♀♀
0	.6232	.5924	.4759	.5771
1	.7873	.5965	.6449	.6996
2	.7480	.6951	.6294	.7190
3	.6923	.6967	.6519	.7160
4	.6521	.7453	.6104	.6704
5	.6052	.6104	.4903	.6220
6	.5885	.5578	.5184	.4706
7	.6047	.5897	.3192	.4893
8	.4566	.3814	.2820	.3634
9	.3019	.0084	-.0045	-.1765
10	.2515	.1741	-.0598	.1155
11	.3673	.2933	.3526	.0261
12	.5821	.3804	.2651	.1315
13	.3028	.0808	.2092	.1101
14	.2213	.2864	.3283	.2280
15	.1152	.1461	.0909	.1253
16	.1786	.2489	.1051	-.0486
17	.2834	.4002	.3086	.4206
18	.0330	.3517	.1984	.2029
19	-.0258	.3060	.1547	-.1459
20	.2963	.4867	.1240	-.1659
21	.1598	.5443	.1703	.1943
22	.2784	.1615	.1285	.2538
23	.3810	.3391	.0881	.5888
24	.2943	.3540	.1816	.5223
25	.3163	.4348	-.6244	.3874
26	.2081	.1719	-.0839	.1765
27	.1104	.4130	.2068	.2625
28	-.0392	.0826	-.1803	.1341
29	.0907	.2951	-.0753	.1147
30	.1299	-.0147	-.1410	-.0481
31	-.0127	.0613	-.3076	-.0604
32	-.1068	.1370	-.2161	-.1735
33	-.0447	.0009	.1011	-.0159
34	-.2057	-.1532	-.3353	-.1363
35	-.0577	-.1039	.0082	-.0261
36	-.1512	-.1430	-.2941	-.1030
37	-.1023	-.1539	-.4780	-.4527
38	-.0596	-.2176	-.0957	-.0480
39	-.2779	-.2918	.0910	-.0908
40	-.2386	-.0447	-.2124	-.0209
41	-.1081	-.1163	-.1281	-.1366
42	-.2140	-.1828	-.2452	-.1771
43	-.2137	-.0019	-.1846	.2531

Table A35. Correlations Between Gain in Body Weight and Subsequent Body Weight for Rhode Island Red and White Leghorn Males and Females

Weeks (t-1)	RIR		WL	
	♂♂	♀♀	♂♂	♀♀
0	.8225	.8413	.8027	.8063
1	.9344	.9094	.9245	.9450
2	.9286	.8784	.8836	.8996
3	.8467	.8374	.8294	.8549
4	.8008	.8047	.8180	.8445
5	.7902	.8359	.7881	.8158
6	.7282	.7528	.7382	.7668
7	.7719	.8125	.7260	.7196
8	.6931	.6776	.5565	.6567
9	.6803	.5749	.4898	.5149
10	.4932	.2088	.2276	-.0534
11	.5218	.4317	.2113	.1190
12	.5446	.4088	.3154	.2474
13	.5647	.4386	.3073	.1163
14	.4690	.2498	.4252	.3168
15	.4890	.3340	.4304	.2130
16	.3965	.2214	.1304	.0963
17	.4259	.1984	.4829	.1550
18	.2874	.3794	.4321	.1361
19	.2964	.3635	.2376	.1933
20	.3372	.4099	.2496	.1436
21	.3402	.5353	.2949	.1996
22	.4668	.5898	.3874	.4435
23	.3856	.2821	.1773	.4669
24	.1867	.1269	.2152	.5526
25	.0235	.0767	.2163	.5317
26	.0624	.1096	.1437	.3439
27	-.1023	.0881	-.0924	.1474
28	.0507	.2852	.0407	.2278
29	.0997	.0070	.1180	.1658
30	-.0153	.1390	.2139	.0600
31	.0949	.1208	.1500	.0202
32	.0158	.1258	-.0859	.2083
33	.1489	.2613	.0979	.2020
34	-.0720	.1279	.1565	.1143
35	-.1135	.1476	-.0454	.1821
36	.0985	.1543	.1088	.1690
37	-.0582	.2074	.1262	.1593
38	-.0901	.0601	-.1202	.0150
39	-.0800	.2078	.0971	.1201
40	.0626	-.0205	-.0490	.1654
41	-.0569	.1500	.1305	.0153
42	.2439	.1429	.0370	.1817
43	.1524	.2122	-.0880	-.0003
44	-.1826	.1917	.1499	-.0588

Table A36. Correlations Between Body Weight and Subsequent Gain in Body Weight for Rhode Island Red and White Leghorn Males and Females

Weeks (t-1)	RIR		WL	
	♂♂	♀♀	♂♂	♀♀
0	-.0092	-.0267	-.2381	-.1393
1	.5336	.4857	.4791	.5922
2	.7353	.6056	.5980	.6746
3	.6581	.6029	.5607	.6695
4	.6076	.5826	.6153	.6876
5	.6123	.7009	.6069	.6808
6	.5460	.6101	.5682	.6234
7	.6433	.6964	.5566	.5884
8	.5529	.5526	.3669	.5340
9	.5603	.4283	.3217	.3411
10	.2676	-.0126	-.0037	-.2431
11	.3255	.2685	-.0282	-.0829
12	.4007	.2374	.0735	.0379
13	.4341	.2558	.0123	-.1271
14	.2723	.0535	.2095	.1008
15	.3216	.1551	.2245	-.0197
16	.2362	.0715	-.0720	-.1047
17	.2837	.0648	.2974	-.0440
18	.1550	.2759	.2821	-.0293
19	.1172	.2327	.0915	.0337
20	.1730	.2773	.0955	-.0095
21	.2076	.3738	.1598	.0635
22	.3477	.4326	.2705	.2894
23	.2809	.0879	.0549	.3237
24	.0711	-.1027	.0747	.3858
25	-.0795	-.1872	.0107	.3524
26	-.0504	-.1667	-.0571	.1084
27	-.2213	-.1905	-.2399	-.1359
28	-.0976	.0448	-.0826	-.0586
29	-.0049	-.2176	-.0012	-.0721
30	-.0947	-.0366	.1260	-.1434
31	.0176	-.0519	.0594	-.1611
32	-.1138	-.0547	-.1743	.0068
33	.0521	.1121	-.0633	.0237
34	-.1658	-.0029	.0624	-.0216
35	-.1930	.0162	-.1317	.0404
36	.0062	.0387	.0132	.0114
37	-.1423	.0637	.0189	.0158
38	-.1807	-.1000	-.2187	-.1395
39	-.1558	.0501	.0015	-.0152
40	-.0444	-.1910	-.1287	-.0106
41	-.1344	-.0227	.0293	-.1370
42	.1654	-.0029	-.0500	.0120
43	.0661	.0537	-.0932	-.1699
44	-.2688	.0282	.0451	-.2612

APPENDIX B

SUPPLEMENTARY FIGURES, CHAPTER I

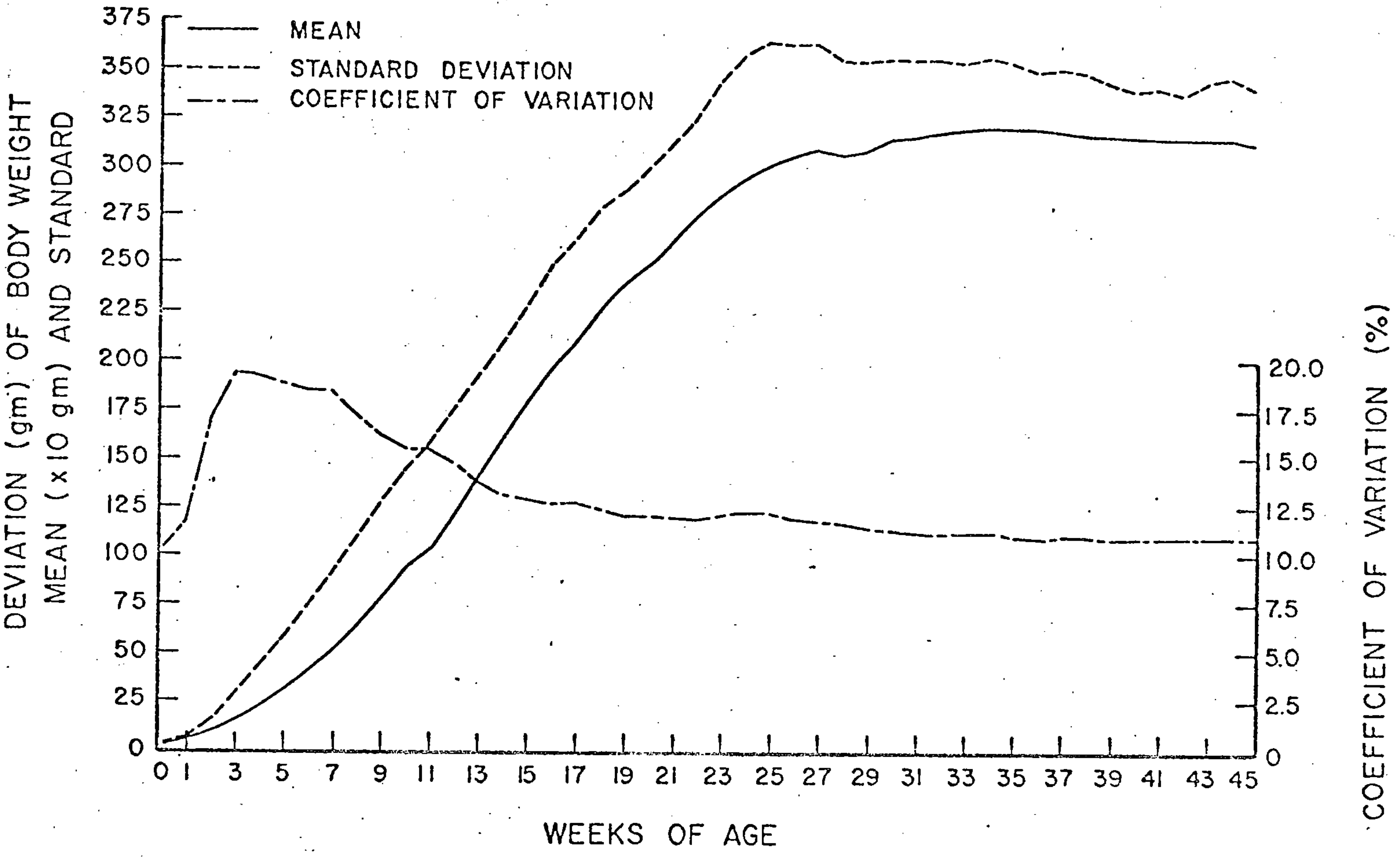

Figure B1. Means, Standard Deviations and Phenotypic Coefficients of Variation of Weekly Body Weights for Rhode Island Red Males

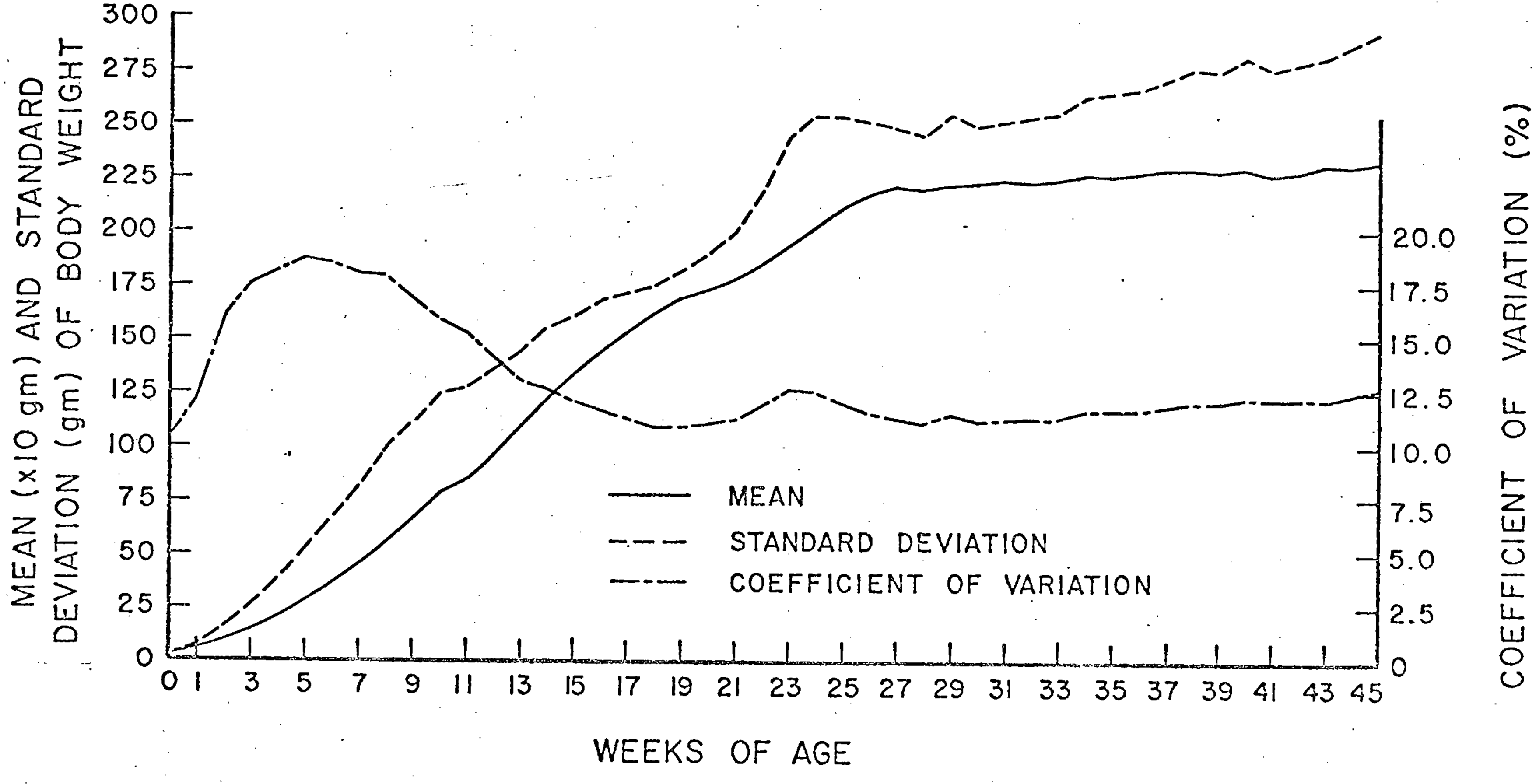

Figure B2. Means, Standard Deviations and Phenotypic Coefficients of Variation of Weekly Body Weights for Rhode Island Red Females

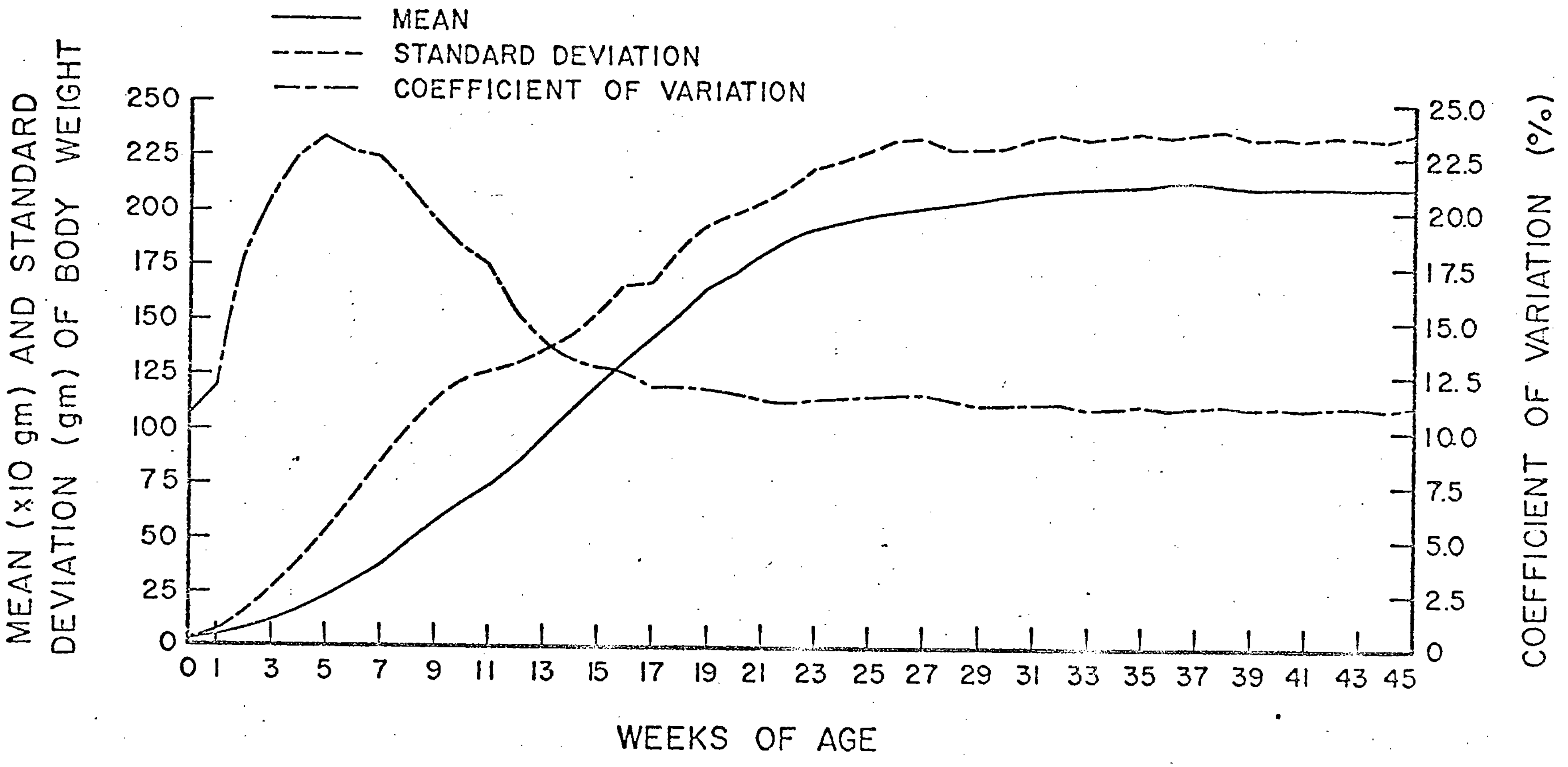

Figure B3. Means, Standard Deviations and Phenotypic Coefficients of Variation of Weekly Body Weights for White Leghorn Males

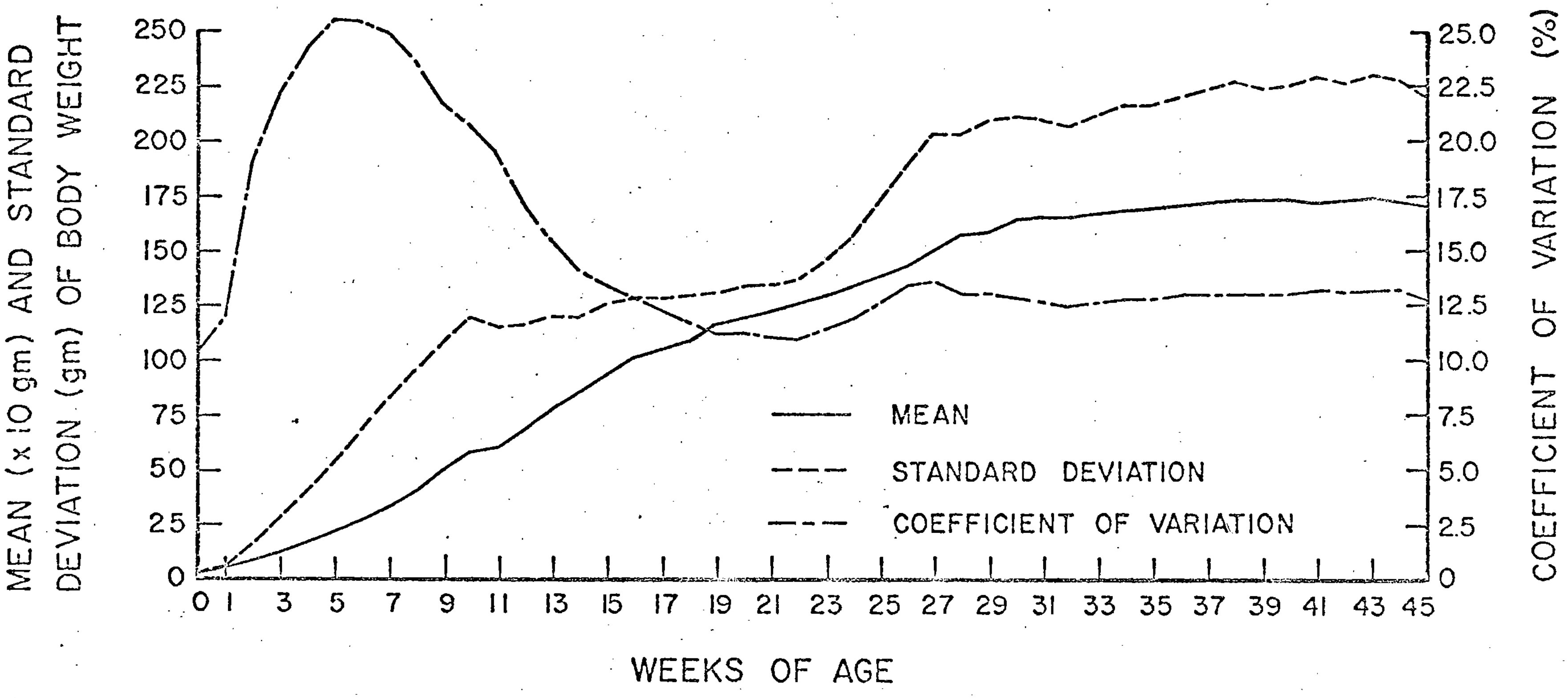

Figure B4. Means, Standard Deviations and Phenotypic Coefficients of Variation of Weekly Body Weights for White Leghorn Females

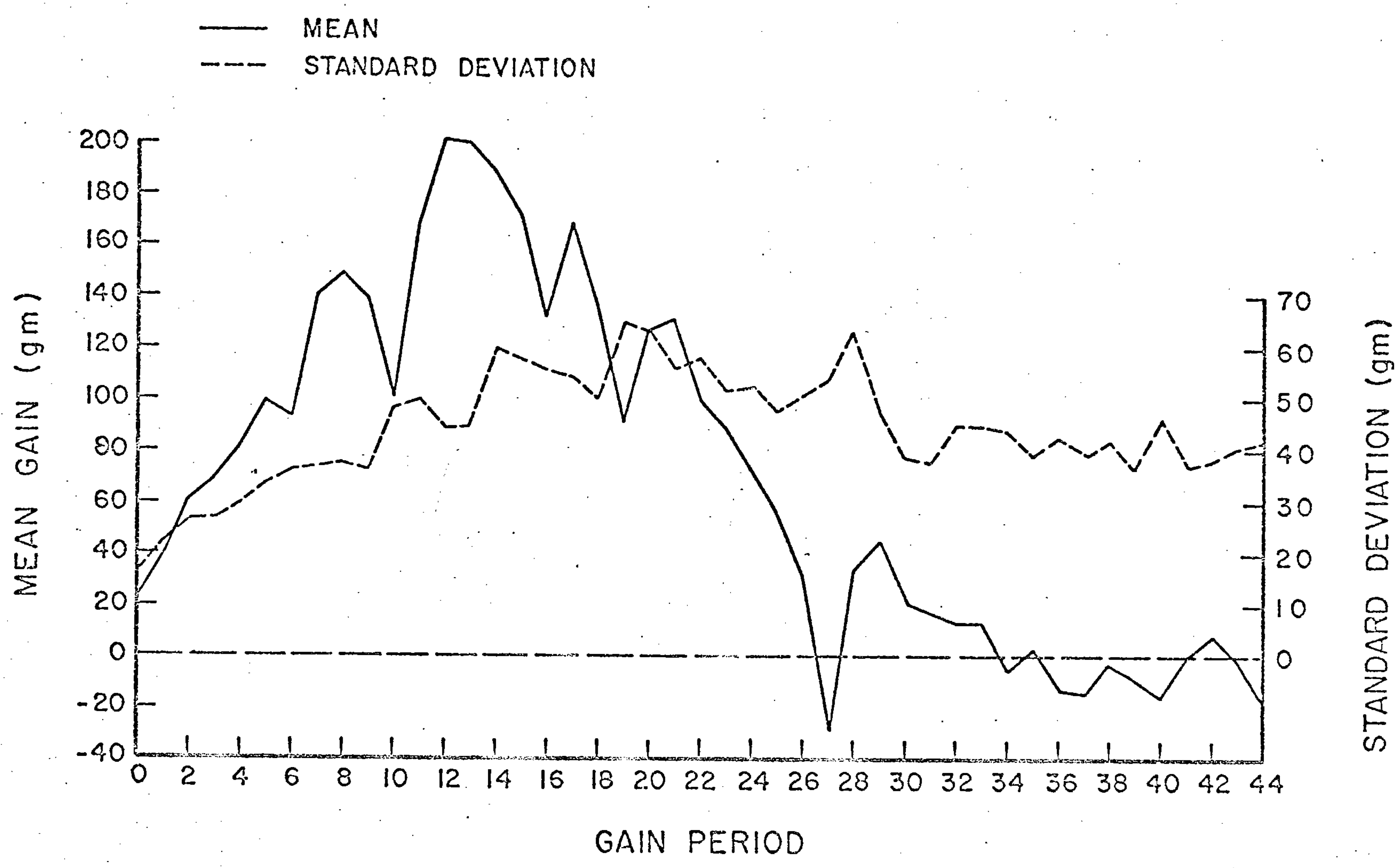

Figure B5. Means and Standard Deviations of Weekly Gains in Body Weight for Rhode Island Red Males

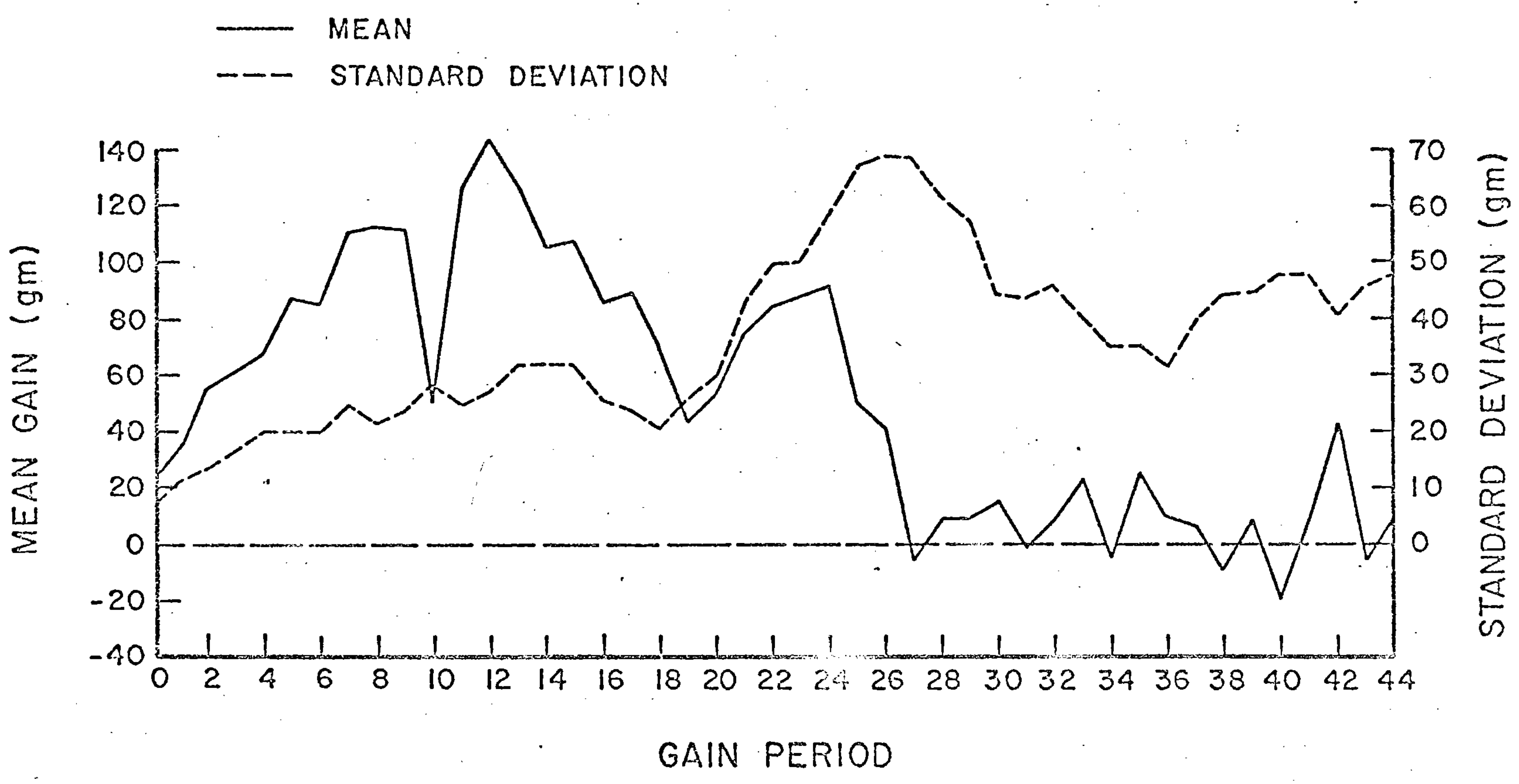

Figure B6. Means and Standard Deviations of Weekly Gains in Body Weight for Rhode Island Red Females

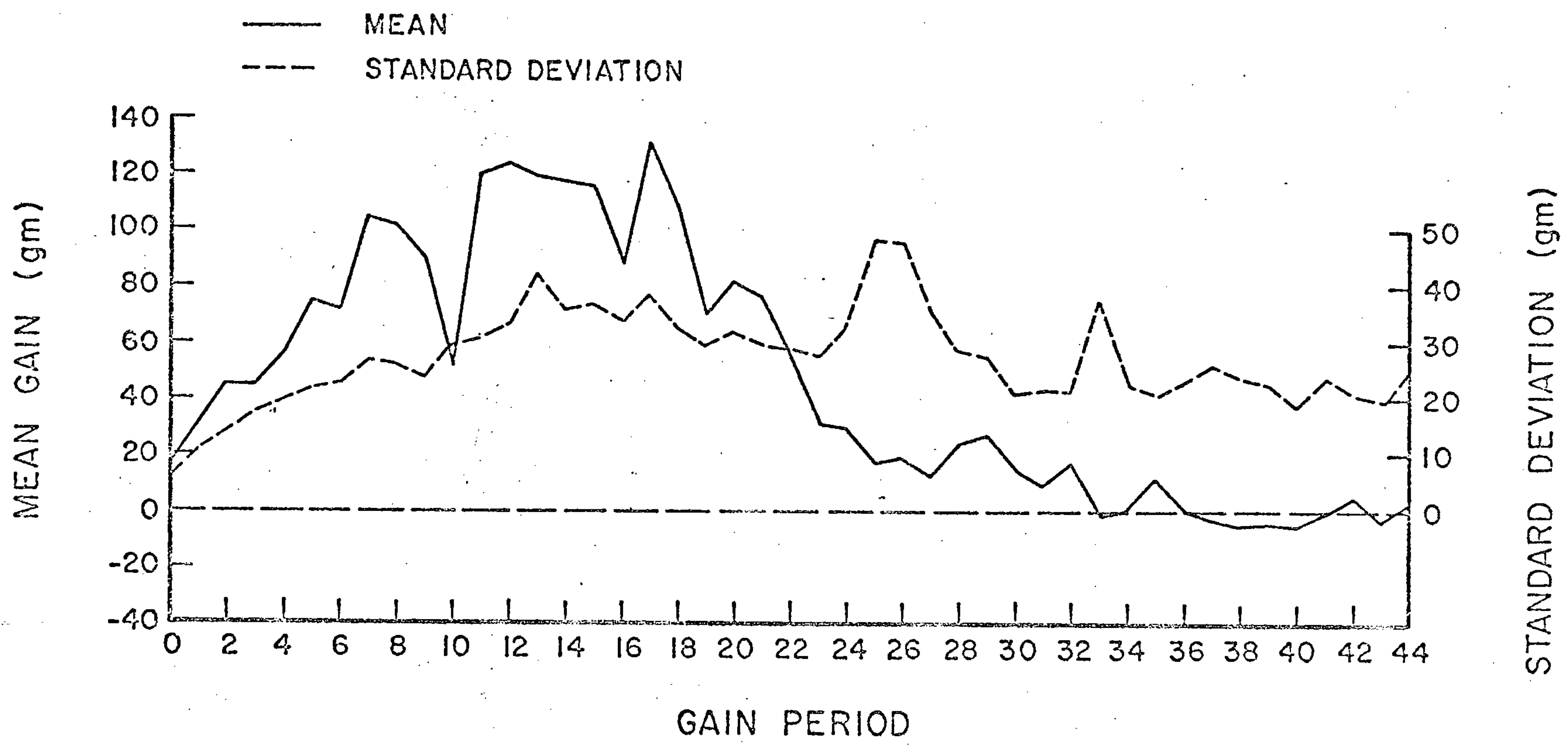

Figure B7. Means and Standard Deviations of Weekly Gains in Body Weight for White Leghorn Males

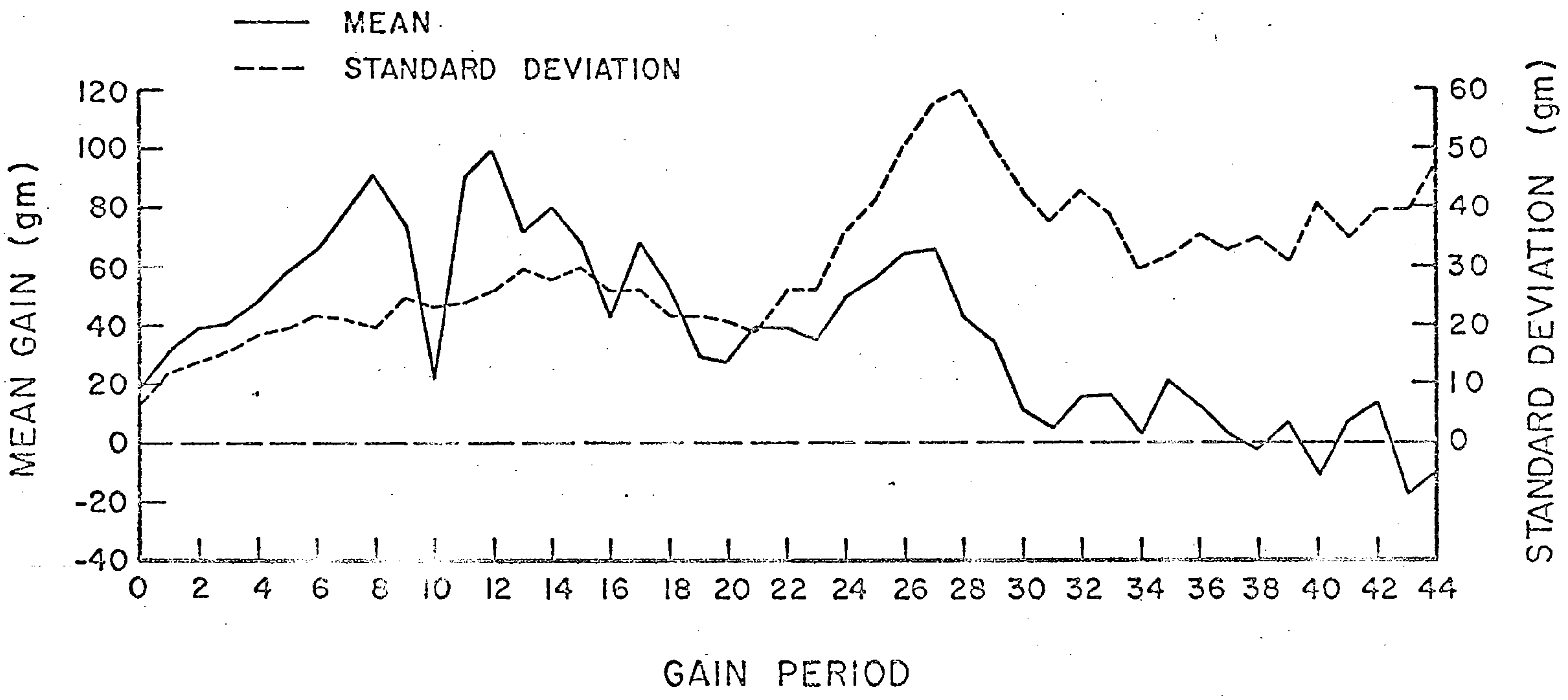

Figure B8. Means and Standard Deviations of Weekly Gains in Body Weight for White Leghorn Females

APPENDIX C

SUPPLEMENTARY TABLES, CHAPTER II

Table Cl. Observed and Theoretical Mean Weights for Rhode Island Red Males using Logistic Function

	Nonlinear Regression			Order Statistics		
Weeks of age	Observed Weights	Predicted Weights	Difference (O-P)	Observed Weights	Predicted Weights	Difference (O-P)
0	38.8	38.8	0.0	.0121	.0024	.0097
1	60.6	52.3	8.3	.0189	.0036	.0153
2	99.7	70.5	29.2	.0312	.0056	.0256
3	159.0	94.8	64.2	.0498	.0085	.0413
4	227.0	127.1	99.9	.0711	.0130	.0581
5	307.6	169.9	137.7	.0963	.0198	.0765
6	406.8	225.9	180.9	.1274	.0300	.0974
7	499.4	298.6	200.8	.1564	.0452	.1112
8	639.2	391.6	247.6	.2002	.0675	.1327
9	788.0	508.5	279.5	.2468	.0998	.1470
10	926.5	652.1	274.4	.2902	.1450	.1452
11	1027.8	823.9	203.9	.3219	.2061	.1158
12	1193.8	1022.7	171.1	.3739	.2843	.0896
13	1394.5	1244.2	150.3	.4368	.3780	.0588
14	1593.6	1481.0	112.6	.4992	.4819	.0173
15	1780.8	1723.0	57.8	.5578	.5873	-.0295
16	1951.5	1959.2	-7.7	.6113	.6853	-.0740
17	2081.8	2179.8	-98.0	.6521	.7691	-.1170
18	2249.8	2377.3	-127.5	.7048	.8360	-.1312
19	2384.2	2547.7	-163.5	.7469	.8864	-.1395
20	2475.7	2689.9	-214.2	.7755	.9227	-.1427
21	2602.0	2805.6	-203.6	.8151	.9481	-.1320
22	2733.0	2897.5	-164.5	.8562	.9654	-.1092
23	2831.9	2969.2	-137.3	.8871	.9771	-.0900
24	2921.5	3024.6	-103.1	.9152	.9849	-.0697
25	2993.7	3066.7	-73.0	.9378	.9901	-.0523
26	3049.1	3098.6	-49.5	.9552	.9935	-.0383
27	3080.6	3122.5	-41.9	.9651	.9957	-.0306
28	3051.7	3140.4	-88.7	.9560	.9972	-.0412
29	3084.7	3153.8	-69.1	.9663	.9981	-.0318
30	3129.2	3163.7	-34.5	.9803	.9988	-.0185
31	3150.4	3171.1	-20.7	.9869	.9992	-.0123
32	3166.7	3176.5	-9.8	.9920	.9994	-.0074
33	3179.3	3180.6	-1.3	.9960	.9996	-.0036
34	3192.0	3183.6	8.4	1.0000	.9997	.0003
35				.9979	.9998	-.0019
36				.9988	.9999	-.0011
37				.9949	.9999	-.0050
38				.9903	.9999	-.0096
39				.9894	.9999	-.0105
40				.9866	.9999	-.0133
41				.9816	.9999	-.0183
42				.9811	.9999	-.0188
43				.9835	.9999	-.0164
44				.9826	.9999	-.0173
45				.9769	.9999	-.0230

Table C2. Observed and Theoretical Mean Weights for Rhode Island Red Females Using Logistic Function

	Nonlinear Regression			Order Statistics		
Weeks of age	Observed Weights	Predicted Weights	Difference (O-P)	Observed Weights	Predicted Weights	Difference (O-P)
0	38.7	38.7	0.0	.0166	.0054	.0112
1	60.0	51.0	9.0	.0258	.0078	.0180
2	96.1	67.2	28.9	.0414	.0113	.0301
3	146.5	88.4	58.1	.0631	.0163	.0468
4	207.0	115.7	91.2	.0892	.0235	.0657
5	274.3	151.1	123.3	.1182	.0337	.0845
6	360.7	196.3	164.4	.1554	.0482	.1072
7	445.8	253.4	192.4	.1921	.0685	.1236
8	555.8	324.6	231.2	.2395	.0964	.1431
9	667.6	411.7	255.9	.2877	.1341	.1536
10	779.0	516.2	262.7	.3357	.1835	.1522
11	829.0	638.4	190.6	.3573	.2459	.1114
12	954.2	777.1	177.1	.4112	.3212	.0900
13	1096.4	929.2	167.2	.4725	.4070	.0655
14	1222.7	1090.0	132.7	.5270	.4990	.0280
15	1327.3	1253.6	73.7	.5721	.5911	-.0190
16	1434.5	1413.6	20.9	.6183	.6771	-.0588
17	1519.3	1564.0	-44.7	.6548	.7526	-.0978
18	1608.1	1700.4	-92.3	.6931	.8153	-.1222
19	1678.0	1820.0	-142.0	.7232	.8650	-.1418
20	1720.6	1922.0	-201.4	.7416	.9028	-.1612
21	1772.8	2006.7	-233.9	.7641	.9309	-.1668
22	1846.8	2075.7	-228.9	.7960	.9514	-.1554
23	1935.1	2131.0	-195.9	.8340	.9659	-.1319
24	2022.8	2174.6	-151.8	.8718	.9763	-.1045
25	2113.0	2208.6	-95.6	.9107	.9835	-.0728
26	2162.8	2235.0	-72.2	.9322	.9886	-.0564
27	2203.5	2255.4	-51.9	.9497	.9921	-.0424
28	2197.3	2271.0	-73.7	.9471	.9945	-.0474
29	2207.1	2282.8	-75.7	.9513	.9962	-.0449
30	2216.4	2291.9	-75.5	.9553	.9974	-.0421
31	2231.3	2298.7	-67.4	.9617	.9982	-.0365
32	2229.8	2303.9	-74.1	.9611	.9987	-.0376
33	2237.9	2307.9	-70.0	.9646	.9991	-.0345
34	2261.1	2310.8	-49.7	.9746	.9994	-.0248
35	2255.9	2313.1	-57.2	.9723	.9995	-.0272
36	2270.2	2314.8	-44.6	.9785	.9997	-.0212
37	2280.0	2316.1	-36.1	.9827	.9998	-.0171
38	2286.3	2317.0	-30.7	.9854	.9998	-.0144
39	2276.6	2317.8	-41.2	.9812	.9999	-.0187
40	2286.2	2318.3	-32.1	.9854	.9999	-.0145
41	2266.2	2318.7	-52.5	.9768	.9999	-.0231
42	2274.2	2319.0	-44.8	.9802	.9999	-.0197
43	2316.3	2319.3	-3.0	.9984	.9999	-.0015
44	2310.7	2319.4	-8.7	.9959	.9999	-.0040
45	2320.0	2319.6	0.4	1.0000	.9999	.0001

Table C3. Observed and Theoretical Mean Weights for White Leghorn Males using Logistic Function

	Nonlinear Regression			Order Statistics		
Weeks of age	Observed Weights	Predicted Weights	Difference (O-P)	Observed Weights	Predicted Weights	Difference (O-P)
0	37.9	37.9	0.0	.0178	.0027	.0151
1	54.8	50.0	4.8	.0257	.0042	.0215
2	85.6	65.9	19.7	.0402	.0064	.0338
3	126.8	86.6	40.2	.0595	.0098	.0497
4	171.5	113.5	58.0	.0805	.0150	.0655
5	226.5	148.0	78.5	.1063	.0227	.0836
6	301.0	192.2	108.8	.1413	.0344	.1069
7	371.8	247.8	124.0	.1746	.0516	.1230
8	476.0	316.9	159.1	.2235	.0767	.1469
9	577.0	401.1	175.9	.2709	.1126	.1583
10	666.6	501.6	165.0	.3130	.1624	.1506
11	717.7	618.2	99.5	.3370	.2286	.1084
12	836.7	749.4	87.3	.3929	.3116	.0813
13	960.1	892.1	68.0	.4509	.4088	.0421
14	1078.5	1041.3	37.1	.5065	.5137	-.0072
15	1194.7	1191.6	3.1	.5611	.6174	-.0563
16	1309.5	1336.8	-27.3	.6150	.7114	-.0964
17	1396.8	1472.0	-75.2	.6560	.7902	-.1342
18	1526.8	1593.3	-66.5	.7170	.8519	-.1349
19	1634.2	1698.8	-64.6	.7675	.8978	-.1303
20	1704.3	1788.0	-83.7	.8004	.9306	-.1302
21	1784.9	1861.6	-76.7	.8382	.9535	-.1153
22	1861.0	1921.2	-60.2	.8740	.9690	-.0950
23	1916.5	1968.6	-52.1	.9001	.9795	-.0794
24	1947.1	2006.0	-58.9	.9144	.9865	-.0721
25	1976.8	2035.0	-58.2	.9284	.9911	-.0627
26	1994.0	2057.5	-63.5	.9365	.9941	-.0576
27	2013.8	2074.7	-60.9	.9458	.9961	-.0503
28	2025.9	2087.9	-62.0	.9514	.9974	-.0460
29	2049.4	2097.9	-48.5	.9625	.9983	-.0358
30	2076.2	2105.6	-29.4	.9751	.9989	-.0238
31	2091.2	2111.4	-20.2	.9821	.9992	-.0171
32	2100.4	2115.7	-15.3	.9864	.9995	-.0131
33	2117.8	2119.0	-1.2	.9946	.9996	-.0050
34	2116.0	2121.5	-5.5	.9938	.9998	-.0050
35	2117.3	2123.4	-6.1	.9944	.9998	-.0054
36	2128.7	2124.8	3.9	.9997	.9999	-.0002
37	2129.2	2125.9	3.3	1.0000	.9999	.0001
38				.9987	.9999	-.0012
39				.9962	.9999	-.0037
40				.9943	.9999	-.0056
41				.9920	.9999	-.0079
42				.9919	.9999	-.0080
43				.9944	.9999	-.0055
44				.9926	.9999	-.0073
45				.9938	.9999	-.0061

Table C4. Observed and Theoretical Mean Weights for White Leghorn Females using Logistic Function

	Nonlinear Regression			Order Statistics		
Weeks of age	Observed Weights	Predicted Weights	Difference (O-P)	Observed Weights	Predicted Weights	Difference (O-P)
0	38.1	38.1	0.0	.0218	.0074	.0144
1	56.0	48.3	7.7	.0321	.0102	.0219
2	86.5	61.0	25.5	.0497	.0140	.0357
3	125.0	77.0	48.0	.0718	.0193	.0525
4	164.5	97.0	67.5	.0945	.0265	.0680
5	211.8	121.8	90.0	.1216	.0363	.0853
6	269.3	152.3	117.0	.1547	.0495	.1052
7	333.9	189.5	144.4	.1918	.0672	.1246
8	411.4	234.5	176.9	.2363	.0907	.1456
9	501.5	288.2	213.3	.2881	.1212	.1669
10	575.7	351.3	224.4	.3307	.1602	.1705
11	596.9	424.2	172.7	.3429	.2087	.1342
12	686.6	506.7	179.9	.3945	.2673	.1272
13	785.2	598.0	187.2	.4511	.3353	.1158
14	856.7	696.4	160.2	.4922	.4109	.0813
15	936.1	799.7	136.4	.5378	.4910	.0468
16	1002.7	905.1	97.6	.5761	.5716	.0045
17	1044.9	1009.4	35.5	.6003	.6485	-.0482
18	1112.3	1109.8	2.5	.6391	.7184	-.0793
19	1164.9	1203.7	-38.8	.6693	.7792	-.1099
20	1193.6	1289.3	-95.7	.6858	.8299	-.1441
21	1220.4	1365.5	-145.1	.7012	.8709	-.1697
22	1259.3	1431.9	-172.6	.7235	.9032	-.1797
23	1297.8	1488.7	-190.9	.7456	.9280	-.1824
24	1332.7	1536.6	-203.9	.7657	.9469	-.1812
25	1380.8	1576.3	-195.5	.7933	.9610	-.1677
26	1435.3	1609.0	-173.7	.8246	.9715	-.1467
27	1499.2	1635.6	-136.4	.8614	.9792	-.1178
28	1563.8	1657.1	-9.3	.8985	.9849	-.0864
29	1606.5	1674.3	-67.8	.9230	.9890	-.0660
30	1640.8	1688.1	-47.3	.9427	.9920	-.0493
31	1652.2	1699.1	-46.9	.9493	.9942	-.0449
32	1657.0	1707.8	-50.8	.9520	.9958	-.0438
33	1671.9	1714.7	-42.8	.9606	.9969	-.0363
34	1688.1	1720.2	-32.1	.9699	.9978	-.0279
35	1691.3	1724.5	-33.2	.9717	.9984	-.0267
36	1711.9	1727.9	-16.0	.9836	.9988	-.0152
37	1724.1	1730.6	-6.5	.9906	.9991	-.0085
38	1726.8	1732.7	-5.9	.9921	.9994	-.0073
39	1724.2	1734.3	-10.1	.9906	.9995	-.0089
40	1731.0	1735.6	-4.6	.9945	.9996	-.0051
41	1719.6	1736.7	-17.1	.9880	.9997	-.0117
42	1727.3	1737.5	-10.2	.9924	.9998	-.0074
43	1740.4	1738.1	2.3	1.0000	.9998	.0002
44				.9904	.9999	-.0095
45				.9842	.9999	-.0157

Table C5. Means of Weekly Body Weights for Rhode Island Red and White Leghorn Males and Females

Weeks	RIR		WL	
of age	♂♂	♀♀	♂♂	♀♀
0	38.8	38.7	37.9	38.1
1	60.6	60.0	54.8	56.0
2	99.7	96.1	85.6	86.5
3	159.0	146.5	126.8	125.0
4	227.0	207.0	171.5	164.5
5	307.6	274.3	226.5	211.8
6	406.8	360.7	301.0	269.3
7	499.4	445.8	371.8	333.9
8	639.2	555.8	476.0	411.4
9	788.0	667.6	577.0	501.5
10	926.5	779.0	666.6	575.7
11	1027.8	829.0	717.7	596.9
12	1193.8	954.2	836.7	686.6
13	1394.5	1096.4	960.1	785.2
14	1593.6	1222.7	1078.5	856.7
15	1780.8	1327.3	1194.7	936.1
16	1951.5	1434.5	1309.5	1002.7
17	2081.8	1519.3	1396.8	1044.9
18	2249.8	1608.1	1526.8	1112.3
19	2384.2	1678.0	1634.2	1164.9
20	2475.7	1720.6	1704.3	1193.6
21	2602.0	1772.8	1784.9	1220.4
22	2733.0	1846.8	1861.0	1259.3
23	2831.9	1935.1	1916.5	1297.8
24	2921.5	2022.8	1947.1	1332.7
25	2993.7	2113.0	1976.8	1380.8
26	3049.1	2162.8	1994.0	1435.3
27	3080.6	2203.5	2013.8	1499.2
28	3051.7	2197.3	2025.9	1563.8
29	3084.7	2207.1	2049.4	1606.5
30	3129.2	2216.4	2076.2	1640.8
31	3150.4	2231.3	2091.2	1652.2
32	3166.7	2229.8	2100.4	1657.0
33	3179.3	2237.9	2117.8	1671.9
34	3192.0	2261.1	2116.0	1688.1
35	3185.5	2255.9	2117.3	1691.3
36	3188.4	2270.2	2128.7	1711.9
37	3175.8	2280.0	2129.2	1724.1
38	3161.3	2286.3	2126.6	1726.8
39	3158.3	2276.6	2121.3	1724.2
40	3149.4	2286.2	2117.1	1731.0
41	3133.3	2266.2	2112.3	1719.6
42	3133.7	2274.2	2112.0	1727.3
43	3139.7	2316.3	2117.3	1740.4
44	3136.6	2310.7	2113.6	1723.8
45	3118.3	2320.0	2116.2	1713.0

APPENDIX D

SUPPLEMENTARY FIGURES, CHAPTER II

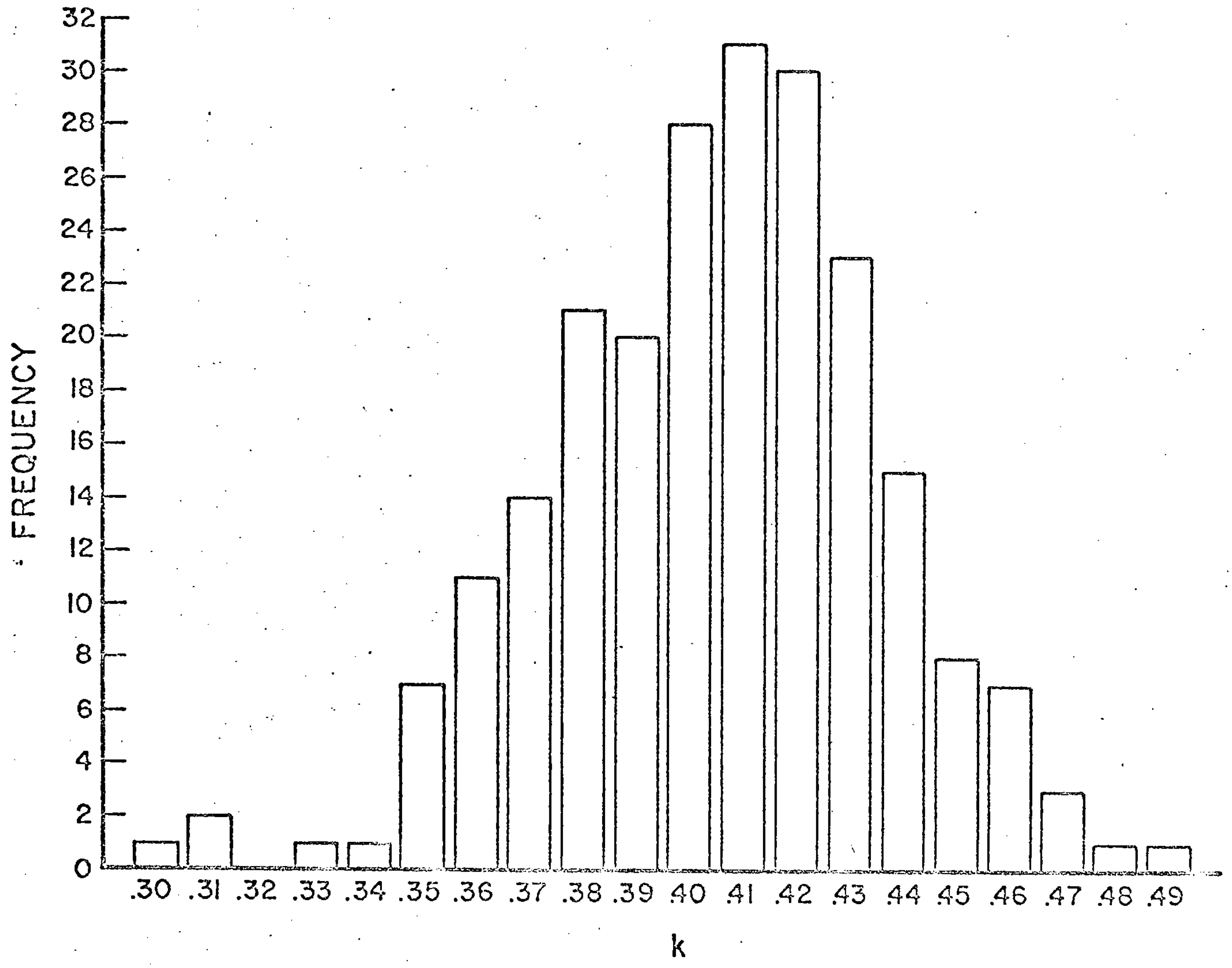

Figure D1. Frequency Distribution of k Values in the Rhode Island Red Males

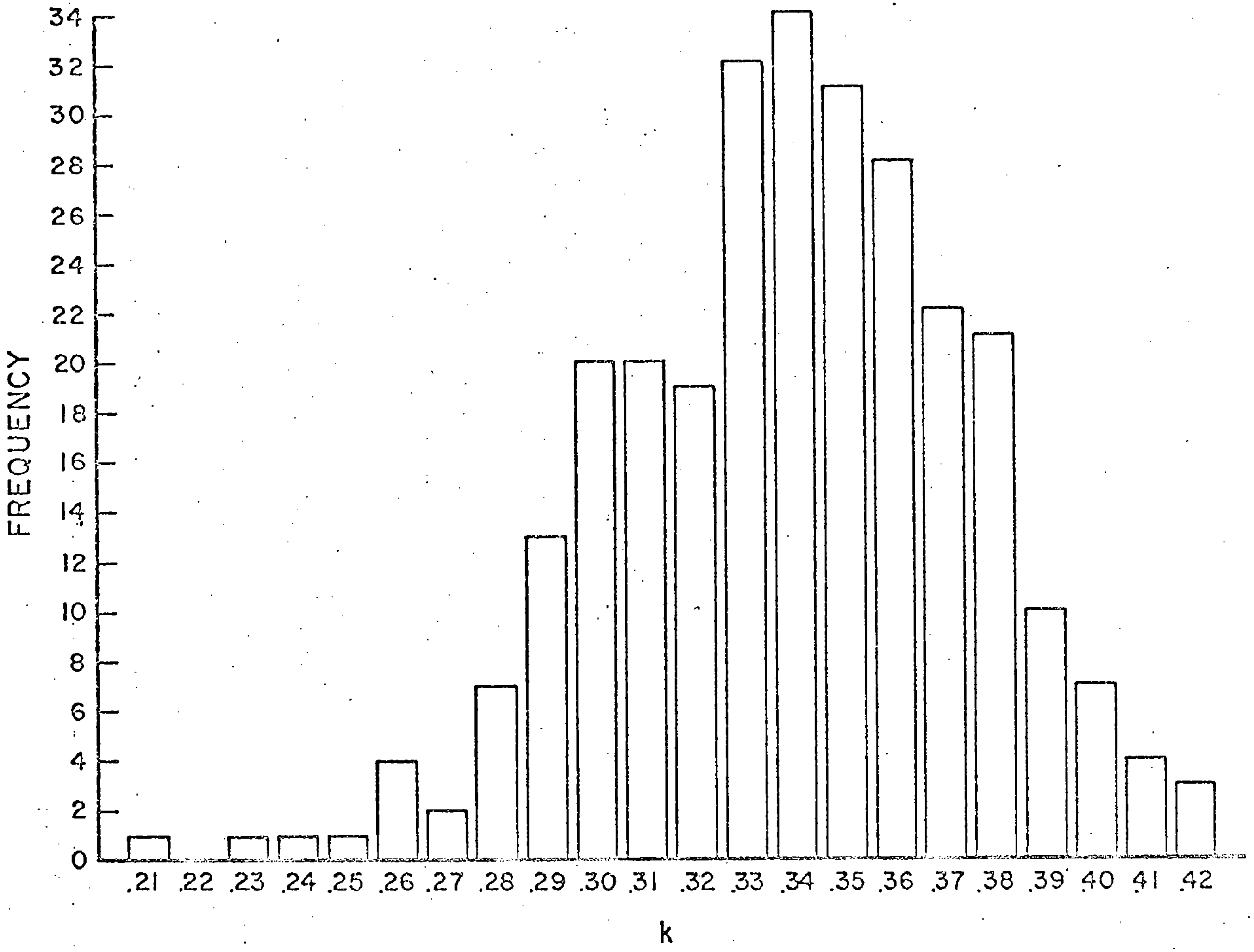

Figure D2. Frequency Distribution of k Values in the Rhode Island Red Females

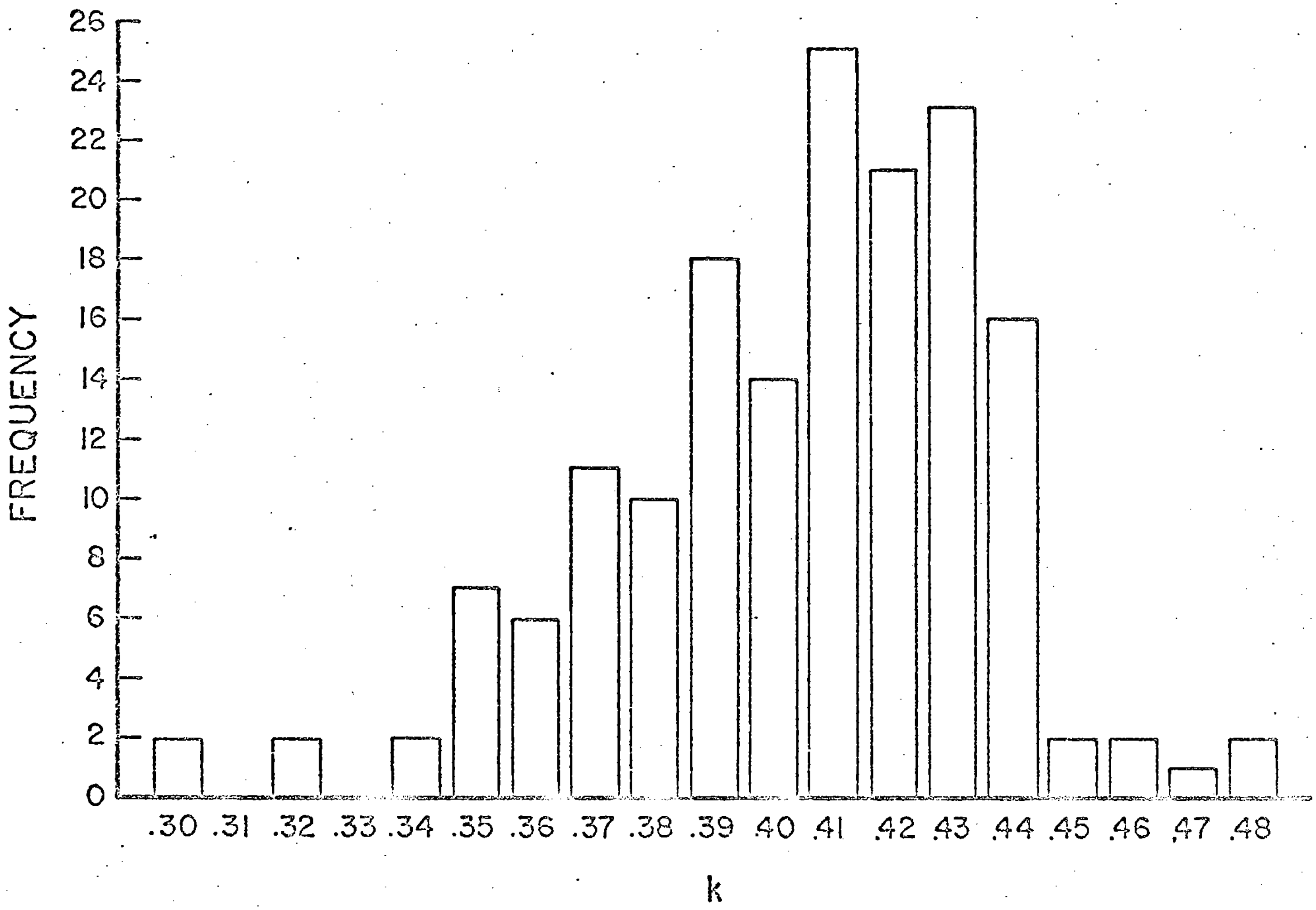

Figure D3. Frequency Distribution of k Values in the White Leghorn Males

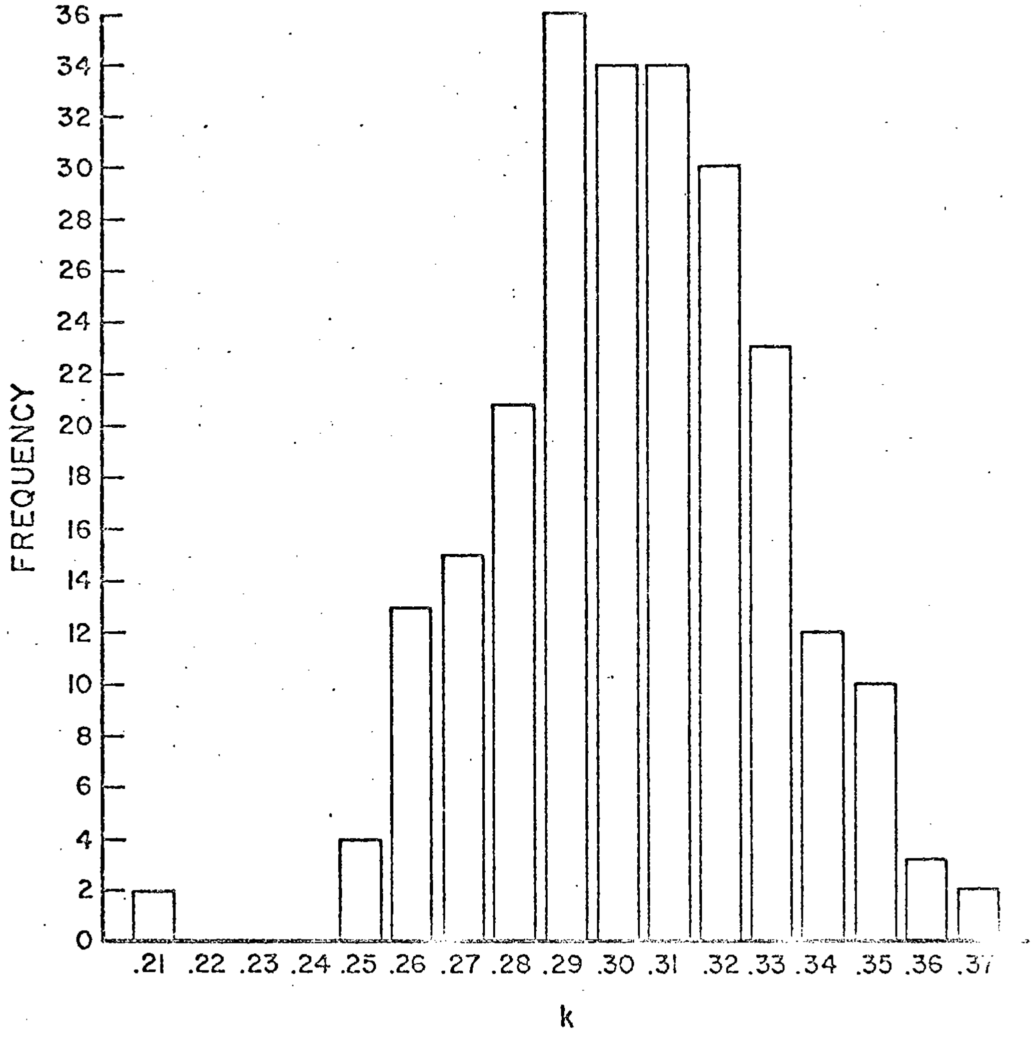

Figure D4. Frequency Distribution of k Values in the White Leghorn Females

VITA

VITA

Michael Grossman, born in New York City on the twenty-first day of December 1940, is the younger of two sons of Benjamin H. and Alice B. Grossman. He attended public schools in The Bronx, graduating from W.H. Taft High School in 1958. He entered Hunter College of The City of New York in September of that year, transferring to The City College of New York in September, 1959. He was graduated with a B.S. degree in June, 1962.

In September, 1963, he began his graduate studies at Virginia Polytechnic Institute, Blacksburg, Virginia. He received his M.S. degree, under the guidance of Dr. Paul B. Siegel, in June, 1965.

His graduate studies at Purdue University began in June, 1965. He became a doctoral candidate on January 5, 1968.

He is a member of the following scientific and professional societies: Sigma Xi, Phi Sigma, The Biometric Society, The Genetic Society of America, The American Genetic Association and Poultry Science Association.