Introductory Models, Effective Population Size

Models

- Intentional simplification of complex relationships
  - Eliminate extraneous detail, focus on key parameters
  - Appropriate and useful first approximations
- Evaluate fit of data to model
  - Poor fit may implicate violation of model assumptions
  - Refining of models tells us which parameters most important
- Population genetics relies heavily on mathematical models
  - Specify the mathematical relationships among parameters that characterize a population

Random Mating

- One of the most important models in population genetics
- Frequency of mating pairs determined by genotype frequencies

Male Genotype Frequency	Female Genotype Frequency		
	A_1A_1 (P_F)	A_1A_2 (H_F)	A_2A_2 (Q_F)
A_1A_1 (P_M)			
A_1A_2 (H_M)			
A_2A_2 (Q_M)			

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A_1A_1 (P_M)	P_MP_F	P_MH_F	P_MQ_F
A_1A_2 (H_M)	H_MP_F	H_MH_F	H_MQ_F
A_2A_2 (Q_M)	Q_MP_F	Q_MH_F	Q_MQ_F

Random Mating

- One of the most important models in population genetics
- Frequency of mating pairs determined by genotype frequencies
- Also called ‘panmictic’ model

Non-overlapping Generations

Birth
Reproductio
n
Death

Generation t -
2

Birth
Reproductio
n
Death

Generation t -
1

Birth
Reproductio
n
Death

Generation t

Hardy-Weinberg Model

- Both models convenient first approximations for complex populations
- What happens when we combine them?
- What are consequences of random mating in a non-overlapping generation model?

Godfrey Harold Hardy

Wilhelm Weinberg

HW Model Assumptions

- Discrete generations
- Random mating
- Sexual reproduction
- Diploid
- Bi-allelic locus
- Allele frequencies equal in males, females
- Large population size
- No migration
- No mutation
- No selection

Hardy-Weinberg Principle

- One of first major principles in population genetics
- Describes relationship between genotype frequency and allele frequency
  - Equilibrium state
- Autosomal locus will alleles A, a
  - Frequencies of A, a: p, q
- Genotypes AA, Aa, aa

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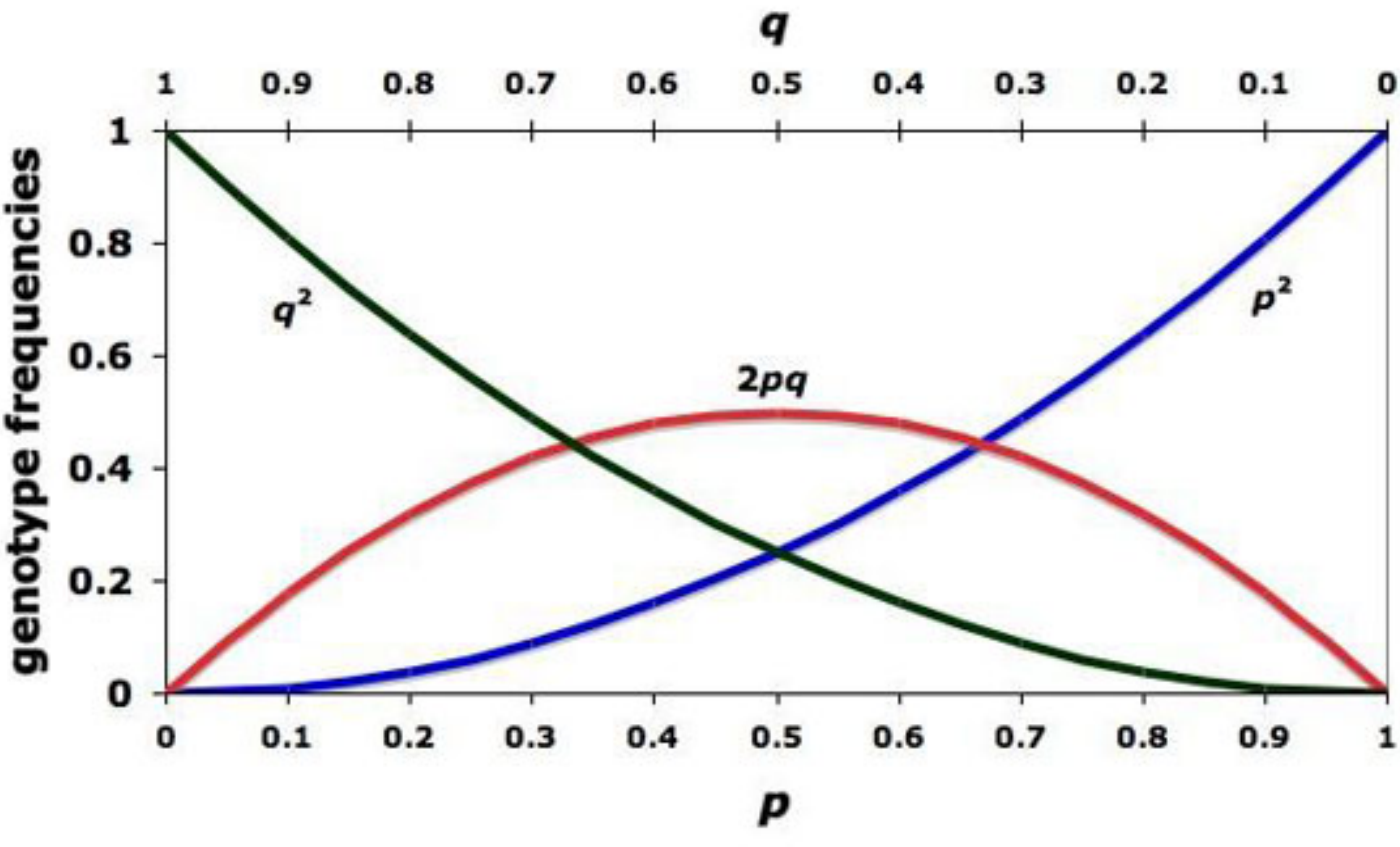
  - HW frequencies: p^2, $2pq$, q^2

HWE Genotype Frequencies



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- Genotypes AA, Aa, aa
  - HW frequencies: p^2, $2pq$, q^2
- Once at HWE, allele & genotype freq constant

Random Genetic Drift

- Hardy-Weinberg equilibrium predicts:
  - 1) Allele frequencies remain constant
  - 2) Genotype frequencies predicted by allele frequencies
- HW model assumes infinite population size
- With finite population size, allele frequencies change over time due to sampling
- Random genetic drift: stochastic change in allele frequencies due to finite sampling of gametes

Random Genetic Drift

- Haploid population of size N
- Two alleles: A, a
- At generation t
  - Frequency of A is p
- Frequency of a is $q = (1-p)$

What is frequency of A at generation t + 1?

Random Genetic Drift

In generation t, freq(A) = p, freq(a) = $(1-p)$

Random Genetic Drift

In generation t, freq(A) = p, freq(a) = $(1-p)$

- Randomly select 1 individual to be parent

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  - Pr(1A) =

Random Genetic Drift

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- Randomly select 1 individual to be parent
  - Pr(1A) = *p*

Random Genetic Drift

In generation t, freq(A) = p, freq(a) = (1-p)

- Randomly select 1 individual to be parent
  - Pr(1A) = p
  - Pr(0A) =

Random Genetic Drift

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  - Pr(1A) = p
  - Pr(0A) = $(1 - p)$

Random Genetic Drift

In generation t, freq(A) = p, freq(a) = (1-p)

- Randomly select 1 individual to be parent
  - $Pr(1A) = p$
  - $Pr(0A) = (1 - p)$
- Randomly select 2 individuals to be parents

Random Genetic Drift

In generation t, freq(A) = p, freq(a) = (1-p)

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  - Pr(1A) = p
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  - Pr(2A) = p^2

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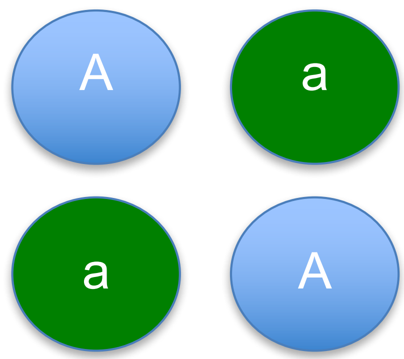
  - – $Pr(2A) = p^2$
  - – $Pr(1A) =$
  - – $Pr(0A) = (1 - p)^2$



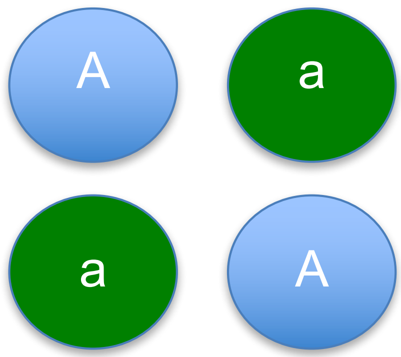
Pr = p(1 – p)

Pr = (1 – p)p

Random Genetic Drift

In generation t, freq(A) = p, freq(a) = (1-p)

- Randomly select 1 individual to be parent
  - $\Pr(1A) = p$
  - $\Pr(0A) = (1 - p)$
- Randomly select 2 individuals to be parents
  - $\Pr(2A) = p^2$
  - $\Pr(1A) = 2p(1-p)$
  - $\Pr(0A) = (1 - p)^2$



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Pr = (1 – p)p

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  - $Pr(1A) = p$
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- Randomly select 2 individuals to be parents
  - $Pr(2A) = p^2$
  - $Pr(1A) = 2p(1-p)$
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- Randomly select 3 individuals to be parents

Random Genetic Drift

In generation t, freq(A) = p, freq(a) = (1-p)

- Randomly select 1 individual to be parent
  - Pr(1A) = p
  - Pr(0A) = $(1 – p)$
- Randomly select 2 individuals to be parents
  - Pr(2A) = p^2
  - Pr(1A) = $2p(1-p)$
  - Pr(0A) = $(1 – p)^2$
- Randomly select 3 individuals to be parents
  - Pr(3A) =
  - Pr(2A) =
  - Pr(1A) =
  - Pr(0A) =

Random Genetic Drift

In generation t, freq(A) = p, freq(a) = (1-p)

- Randomly select 1 individual to be parent
  - $Pr(1A) = p$
  - $Pr(0A) = (1 - p)$
- Randomly select 2 individuals to be parents
  - $Pr(2A) = p^2$
  - $Pr(1A) = 2p(1-p)$
  - $Pr(0A) = (1 - p)^2$
- Randomly select 3 individuals to be parents
  - $Pr(3A) = p^3$
  - $Pr(2A) = 3p^2(1 - p)$
  - $Pr(1A) = 3p(1 - p)^2$
  - $Pr(0A) = (1 - p)^3$

Random Genetic Drift

In generation t, freq(A) = p, freq(a) = (1-p)

- Randomly select N individuals to be parents

$$\Pr(j\ alleles\ of\ type\ A) = \binom{N}{j} p^{j}(1-p)^{N-j}$$

What is frequency of A at generation t + 1?

Random Genetic Drift

Frequency of A	Generation(t+1)
0/N	$\binom{N}{0}(p_t)^0(1-p_t)^{N-0}$
1/N	$\binom{N}{1}(p_t)^1(1-p_t)^{N-1}$
2/N	$\binom{N}{2}(p_t)^2(1-p_t)^{N-2}$
.	
.	
.	
N/N	$\binom{N}{N}(p_t)^N(1-p_t)^0$

Random Genetic Drift

Frequency of A	Generation(t+1)	Generation (t+2)
0/N	$\binom{N}{0}(p_t)^0(1-p_t)^{N-0}$	$\binom{N}{0}(p_{t+1})^0(1-p_{t+1})^{N-0}$
1/N	$\binom{N}{1}(p_t)^1(1-p_t)^{N-1}$	$\binom{N}{1}(p_{t+1})^1(1-p_{t+1})^{N-1}$
2/N	$\binom{N}{2}(p_t)^2(1-p_t)^{N-2}$	$\binom{N}{2}(p_{t+1})^2(1-p_{t+1})^{N-2}$
.		
.		
.		
N/N	$\binom{N}{N}(p_t)^N(1-p_t)^0$	$\binom{N}{N}(p_{t+1})^N(1-p_{t+1})^0$

Random Genetic Drift

Frequency of A	Generation(t+1)	Generation (t+2)	Generation(t+3)
0/N	$\binom{N}{0}(p_t)^0(1-p_t)^{N-0}$	$\binom{N}{0}(p_{t+1})^0(1-p_{t+1})^{N-0}$	$\binom{N}{0}(p_{t+2})^0(1-p_{t+2})^{N-0}$
1/N	$\binom{N}{1}(p_t)^1(1-p_t)^{N-1}$	$\binom{N}{1}(p_{t+1})^1(1-p_{t+1})^{N-1}$	$\binom{N}{1}(p_{t+2})^1(1-p_{t+2})^{N-1}$
2/N	$\binom{N}{2}(p_t)^2(1-p_t)^{N-2}$	$\binom{N}{2}(p_{t+1})^2(1-p_{t+1})^{N-2}$	$\binom{N}{2}(p_{t+2})^2(1-p_{t+2})^{N-2}$
.			
.			
.			
N/N	$\binom{N}{N}(p_t)^N(1-p_t)^0$	$\binom{N}{N}(p_{t+1})^N(1-p_{t+1})^0$	$\binom{N}{N}(p_{t+2})^N(1-p_{t+2})^0$

Transitions between states are random, but defined by a probability

Transitions have no memory beyond previous step

Random Genetic Drift

Frequency of A	Generation(t+1)	Generation (t+2)	Generation(t+3)
0/N	$\binom{N}{0}(p_t)^0(1-p_t)^{N-0}$	$\binom{N}{0}(p_{t+1})^0(1-p_{t+1})^{N-0}$	$\binom{N}{0}(p_{t+2})^0(1-p_{t+2})^{N-0}$
1/N	$\binom{N}{1}(p_t)^1(1-p_t)^{N-1}$	$\binom{N}{1}(p_{t+1})^1(1-p_{t+1})^{N-1}$	$\binom{N}{1}(p_{t+2})^1(1-p_{t+2})^{N-1}$
2/N	$\binom{N}{2}(p_t)^2(1-p_t)^{N-2}$	$\binom{N}{2}(p_{t+1})^2(1-p_{t+1})^{N-2}$	$\binom{N}{2}(p_{t+2})^2(1-p_{t+2})^{N-2}$
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Transitions between states are random, but defined by a probability

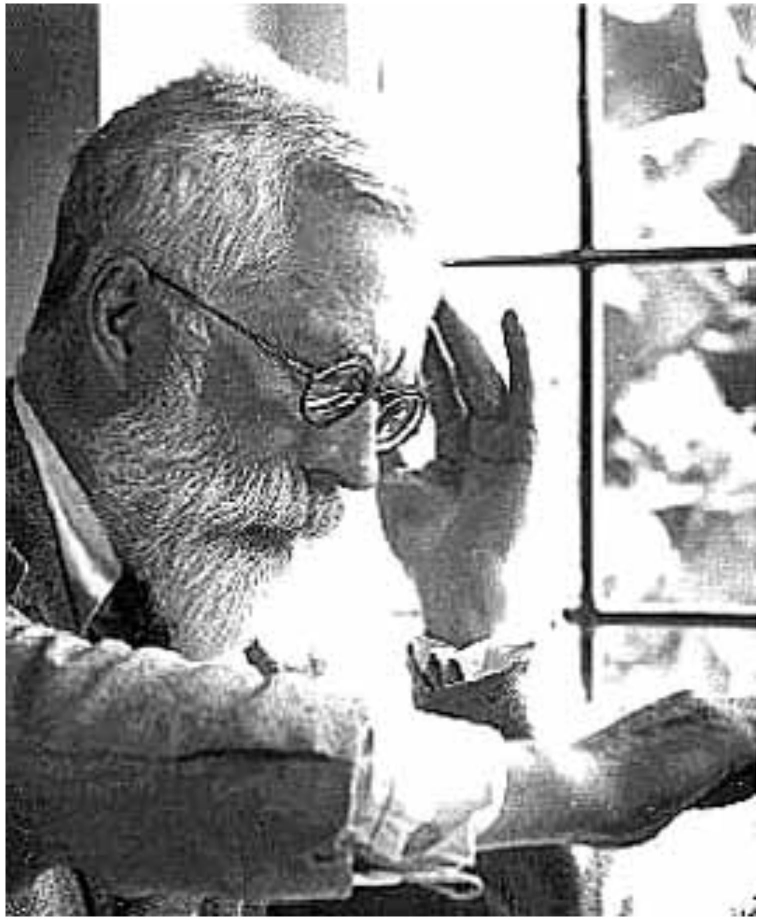
Transitions have no memory beyond previous step

Diploid Model

- N diploid individuals
  - 2N alleles in population
- Two alleles: A, a (frequencies *p*, *q*)
- Randomly draw 2N gametes to found next generation

$$\Pr(j\ alleles\ of\ type\ A) = \binom{2N}{j} \mathrm{p}^{\mathrm{j}}(1\text{-}\mathrm{p})2^{\mathrm{N-j}}$$

Wright-Fisher Model



Wright-Fisher Model

- Assumptions:
  - N diploid organisms (2N alleles)
  - Infinite gametes
  - Discrete Generations
  - Random mating
  - No mutation
  - No selection

$$P_{ij} = \binom{2N}{j}\left(\frac{i}{2N}\right)^{j}\left(1-\frac{i}{2N}\right)^{2N-j} = \binom{2N}{j} p^{j} q^{2N-j}$$

Time, Probability of fixation

- Alleles are eventually fixed or lost
- 2N alleles
  - Each equally likely to fix (selectively equivalent)
  - Pr(fixation) =

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  - Each equally likely to fix (selectively equivalent)
  - Pr(fixation) = 1/2N
  - If i copies of allele, Pr(fixation) = i/2N
- Pr(fixation) = p

Probabilities of fixation, loss

- Alleles are eventually fixed or lost
- 2N alleles
  - Each equally likely to fix (selectively equivalent)
  - Pr(fixation) = 1/2N
  - If *i* copies of allele, Pr(fixation) = *i*/2N
- Pr(fixation) = *p*
- Pr(loss) = 1-*p*

Times to fixation, loss

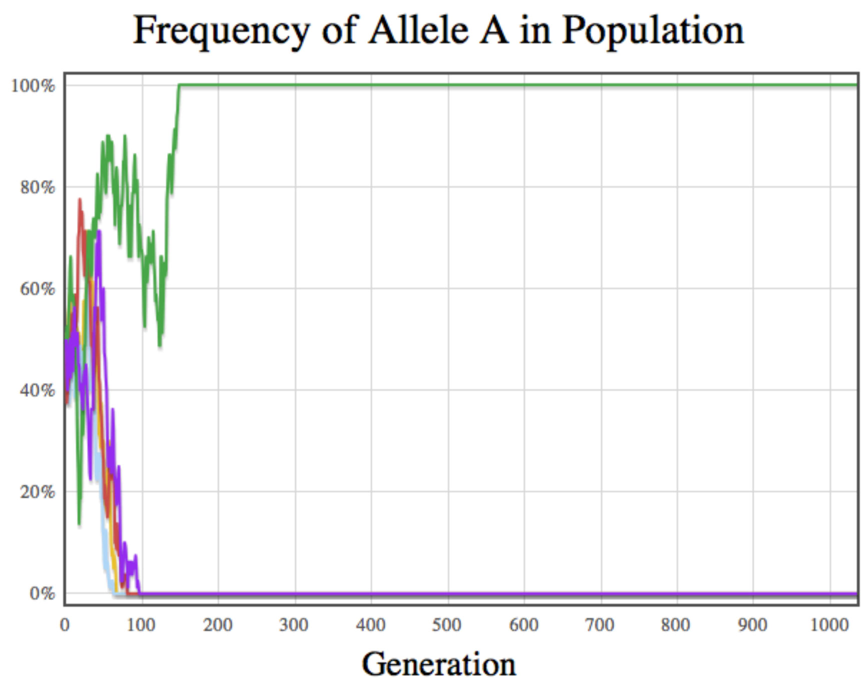
$$t_{fix} = \frac{-4N(1-p)\ln(1-p)}{p}$$

For p = 1/2N, $t_{fix} \approx 4N$

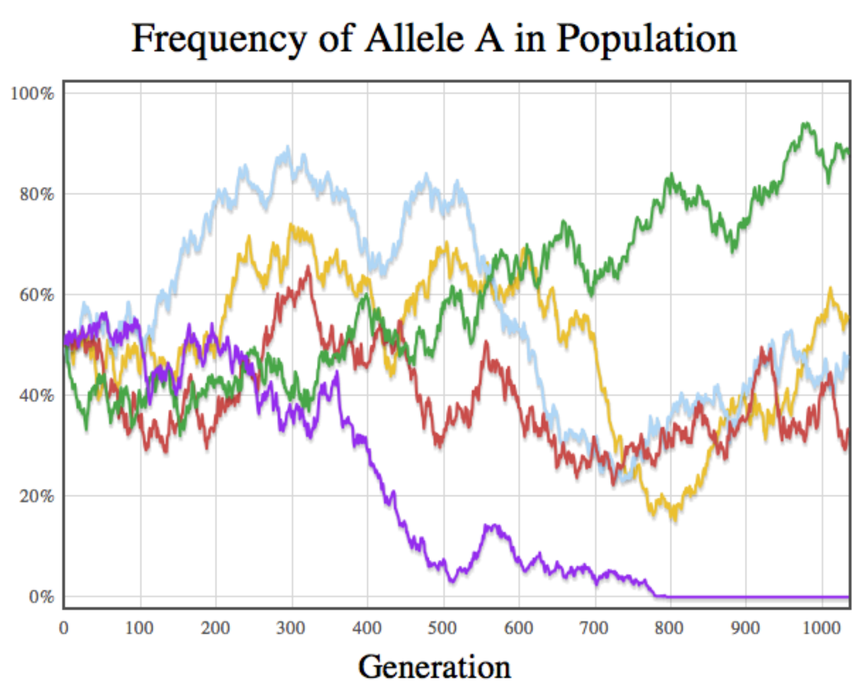
$$t_{loss} = \frac{-4N(p)\ln(p)}{1-p}$$

For p = 1/2N, $t_{loss} \approx 2\ln(2N)$

N = 40



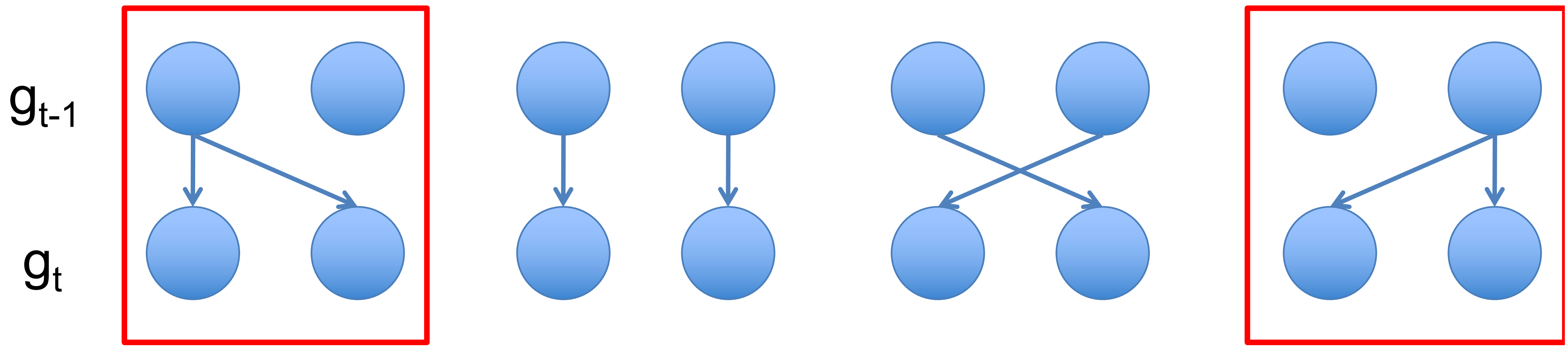
N = 2000



http://scit.us/redlynx/

Decay of Heterozygosity

2N=2



Pr(IBD) = 2/4 = 1/2

Pr(IBD) = 1/2N

Pr(not IBD) = 1 - 1/2N

$$\Pr(IBD_t) = F_t = \boxed{\frac{1}{2N}} + \boxed{(1-\frac{1}{2N})F_{t-1}}$$

$$\text{If } F_0 = 0, F_t = 1-(1-\frac{1}{2N})^t$$

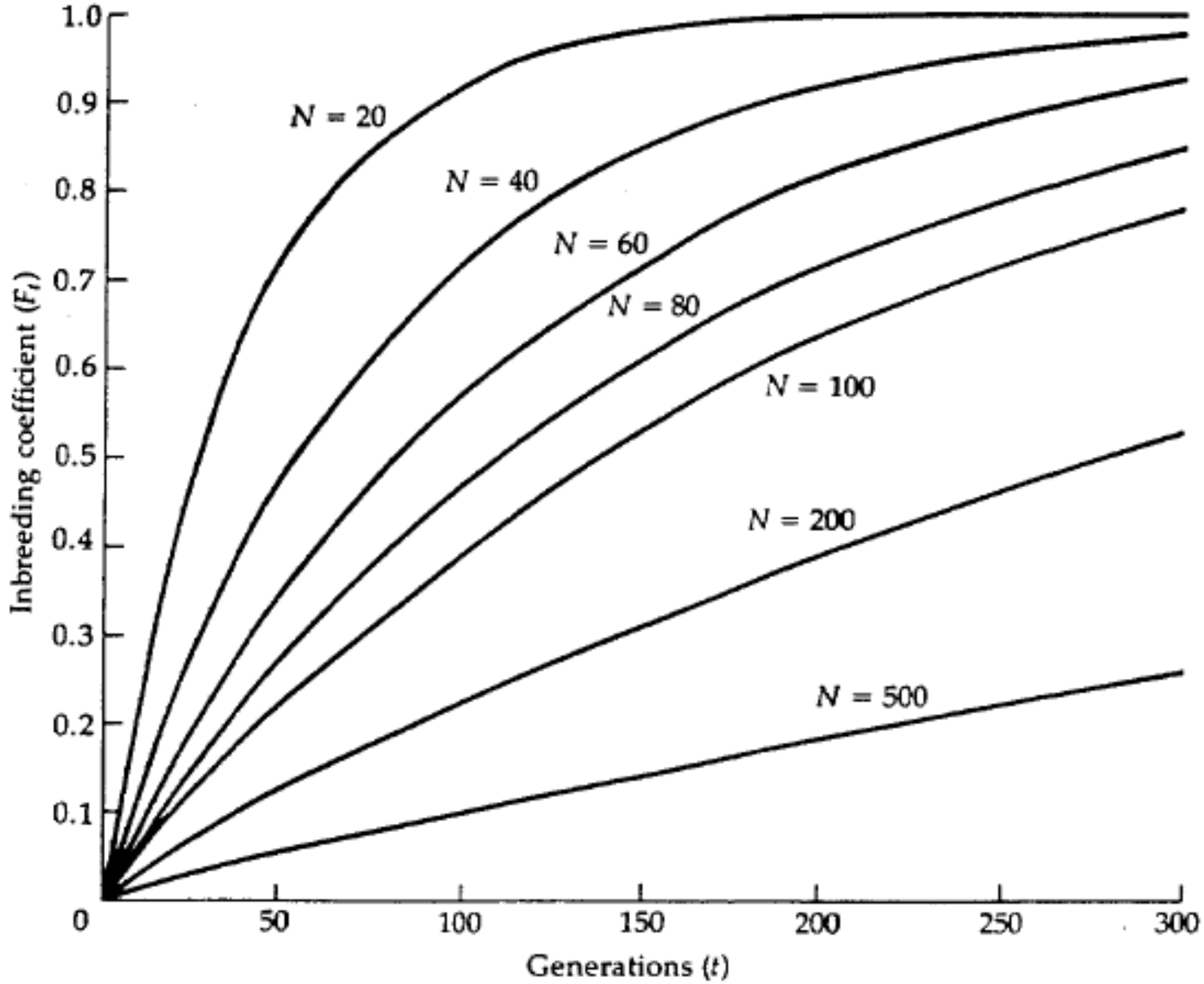


Figure 9. Increase of F_t in ideal populations as a function of time and effective population size N.

Hartl & Clark

Decay of Heterozygosity

$$F_t = 1 - (1 - \frac{1}{2N})^t$$

$$H_t = H_0\left(1 - \frac{1}{2N}\right)^t \approx H_0 e^{-t/2N}$$

Summary of Drift

- Stochastic fluctuations in allele frequencies due to sampling in a finite population
- Described by Wright-Fisher model
- Alleles are ultimately fixed or lost from population
  - Pr(fix) = p; Pr(loss) = 1 – p
  - Time($\text{fix}_{1/2N}$) ≈ 4N; Time($\text{loss}_{1/2N}$) ≈ 2ln(2N)
- H decreases (~1/2N) over time
- Hardy-Weinberg largely still applies
  - Allele frequency changes small
  - Deviation from expected genotype frequencies ~ 1/2N

Habitat loss

- Small, isolated populations are threatened
  - RGD

Habitat loss

- Small, isolated populations are threatened
  - RGD, inbreeding
- Consequences:
  - Reduction in genetic diversity

Genetically depauperate species

Species	Populations (N)	Individuals (N)	Loci (N)	Polymorphic loci (%)	Average heterozygosity	Reference
			Allozyme			
Drosophila	43*	> 100	24	43.1	0.140	*(10)*
Mus musculus	2	87	46	20.5	0.088	*(15)*
Felis catus	1	56	55	22.0	0.076	*(16)*
Homo sapiens	Many	> 100	104	31.7	0.063	*(43–45)*
Acinonyx jubatus	2	55	47	0.0	0.0	




O'Brien et al.

Genetically depauperate species

TABLE 2. Distribution and allele frequency of polymorphic allozyme loci in lions

Population	No. lions scored	Allozyme locus[a] IDH1	TF	PT1	Percent polymorphic loci	Average Heterozygosity[b]
African						
Kruger Park South Africa	15	A = 1.0	a = 0.65 b = 0.35	s = 1.0	7	0.023
Serengeti ecosystem Tanzania, East Africa	27	A = 0.72 B = 0.28	a = 0.52 b = 0.28	s = 1.0	11	0.038
African Zoo lions (Atlas)	18	A = 1.0	a = 0.72 b = 0.28	s = 1.0	7	0.030
Asian						
Indian lions (Gir Forest)	28	B = 1.0	a = 1.0	d = 1.0	0.0	0.0
Indian lions (SSP-studbook)	29	A = 0.72 B = 0.28	a = 0.93 b = 0.07	s = 0.45 d = 0.55	7	0.021

O’Brien et al.

Genetically depauperate species

Number	Date	Location	Microsatellite locus			mtDNA
			043	090	096	
Contemporary						
14	1980s	Big Cypress Swamp	122/122	121/121	203/203	A
67	1980s	Big Cypress Swamp	122/122	121/121	203/203	A
71	1980s	Big Cypress Swamp	122/130	121/121	203/203	A
422	1980s	Big Cypress Swamp	122/122	121/121	203/203	A
426	1980s	Big Cypress Swamp	122/130	121/121	203/203	A
428	1980s	Big Cypress Swamp	122/122	121/121	203/203	A
Museum						
777	1890s	Florida	–	–	–	C
778	1890s	Florida	–	–	–	C
779	1890s	Florida	–	–	–	C
780	1890s	Immokolee	122/124	127/127	203/203	C
785	1898	Sebastian	134/134	–	–	A
787	1898	Sebastian	104/126	–	–	–
792	1922	Allen's River	–	–	–	B

Culver et al. 2008

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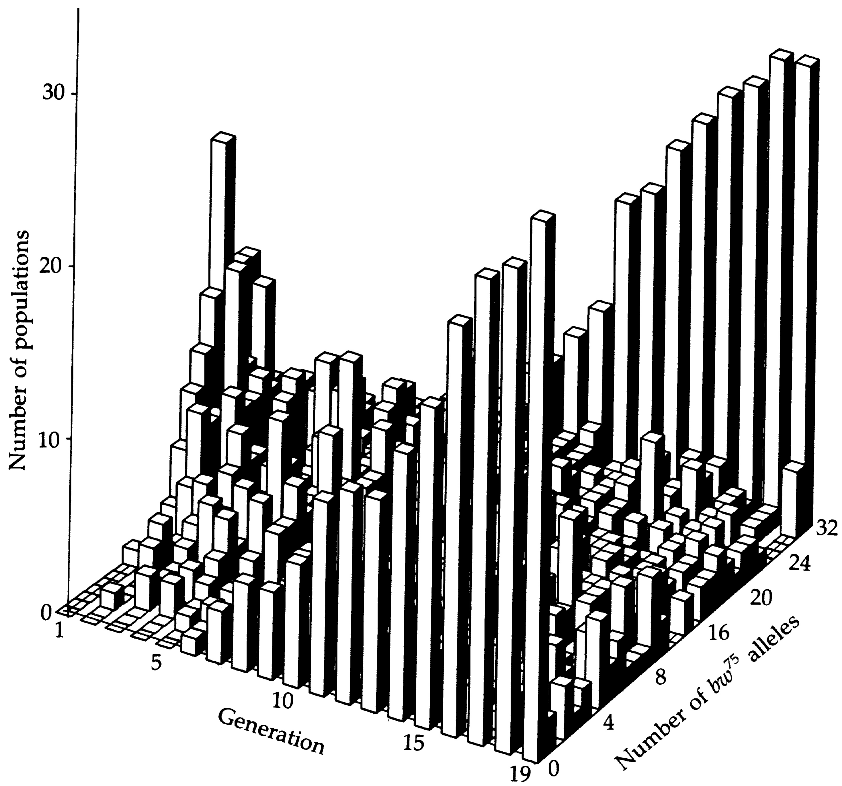
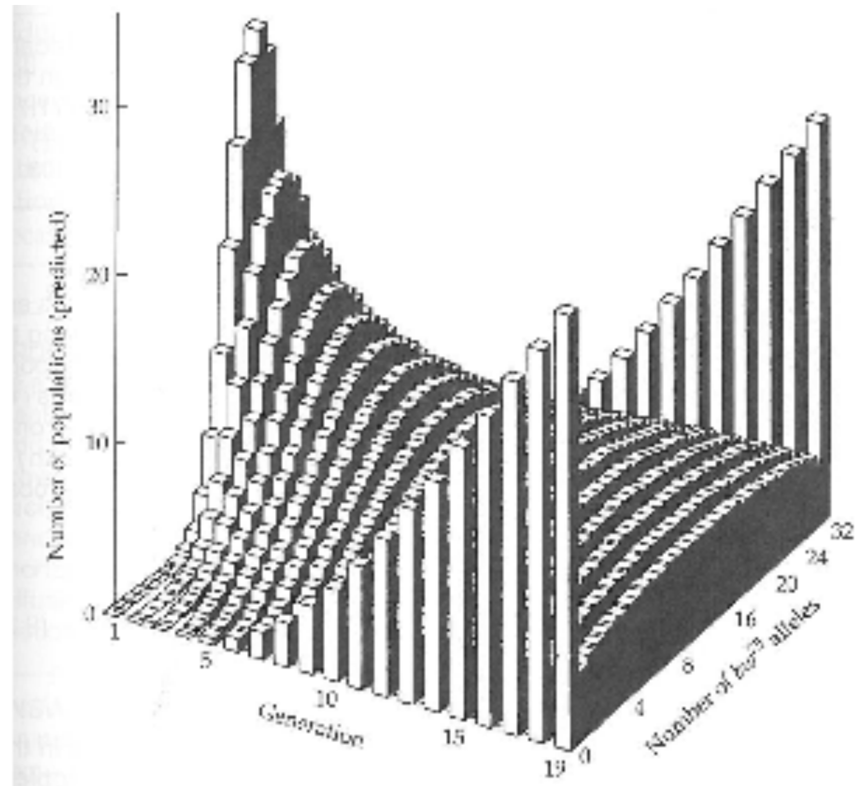
Effective Population Size





Buri 1956

Effective Population Size

$$\mathrm{Var}(p) = \mathrm{Var}\left(\frac{\#A}{2N}\right) = \left(\frac{1}{2N}\right)^2 \mathrm{Var}(\#A)$$

$$= \left(\frac{1}{2N}\right)^2 2Npq$$

$$= \frac{pq}{2N}$$

Effective Population Size

$$\mathrm{Var}(p) = \mathrm{Var}\left(\frac{\#A}{2N}\right) = \left(\frac{1}{2N}\right)^2 \mathrm{Var}(\#A)$$

$$= \left(\frac{1}{2N}\right)^2 2Npq$$

$$= \frac{pq}{2N}$$

- In reality, allele frequency changes > $pq/2N$
  - Fluctuations in population size, $N_m \neq N_f$, *etc.*

Effective Population Size

- Number of individuals in a theoretically ideal population having the same magnitude of drift as the actual population
- Measure 'magnitude' in 3 ways
  - Change in variance of allele frequency (variance N_e)

$$\mathrm{var}(p) = \frac{pq}{2N}$$

$$\overline{\mathrm{var}}(p) = \frac{pq}{2N_e}$$

$$N_e = \frac{pq}{2\overline{\mathrm{var}}(p)}$$

Effective Population Size

- Number of individuals in a theoretically ideal population having the same magnitude of drift as the actual population
- Measure ‘magnitude’ in 3 ways
  - Change in variance of allele frequency (variance N_e)
  - Change in Pr(IBD) (inbreeding N_e)
  - Rate of loss of heterozygosity (eigenvalue N_e)

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  - Rate of loss of heterozygosity (eigenvalue N_e)
- Typically smaller than census size N
  - Sex ratio
  - Variance in reproductive success
  - Population size changes

Relating N, N_e

- Population size changes

$$\frac{1}{N_e} = \frac{1}{t}\left(\frac{1}{N_0} + \frac{1}{N_1} + \ldots + \frac{1}{N}\right)$$

Relating N, N_e

- Population size changes

$$\frac{1}{N_e} = \frac{1}{t}\left(\frac{1}{N_0} + \frac{1}{N_1} + \ldots + \frac{1}{N}\right)$$

- Unequal males, females

$$N = N_m + N_f$$

$$N_e = \frac{4N_m N_f}{N_m + N_f}$$

Hardy-Weinberg Principle

Frequency(A) = p
Frequency(a) = q

Frequency(AA) = P
Frequency(Aa) = H
Frequency(aa) = Q

Mating
AA x AA
AA x Aa
AA x aa
Aa x Aa
Aa x aa
aa x aa

Hardy-Weinberg Principle

Frequency(A) = p
Frequency(a) = q

Frequency(AA) = P
Frequency(Aa) = H
Frequency(aa) = Q

Mating	Frequency of Mating
AA x AA	
AA x Aa	
AA x aa	
Aa x Aa	
Aa x aa	
aa x aa	

Hardy-Weinberg Principle

Frequency(A) = p
Frequency(a) = q

Frequency(AA) = P
Frequency(Aa) = H
Frequency(aa) = Q

Mating	Frequency of Mating
AA x AA	P^2
AA x Aa	
AA x aa	
Aa x Aa	
Aa x aa	
aa x aa	

Hardy-Weinberg Principle

Frequency(A) = p
Frequency(a) = q

Frequency(AA) = P
Frequency(Aa) = H
Frequency(aa) = Q

Mating	Frequency of Mating
AA x AA	P^2
AA x Aa	$2PH$
AA x aa	
Aa x Aa	
Aa x aa	
aa x aa	

Hardy-Weinberg Principle

Frequency(A) = p
Frequency(a) = q

Frequency(AA) = P
Frequency(Aa) = H
Frequency(aa) = Q

Mating	Frequency of Mating
AA x AA	P^2
AA x Aa	$2PH$
AA x aa	$2PQ$
Aa x Aa	
Aa x aa	
aa x aa	

Hardy-Weinberg Principle

Frequency(A) = p
Frequency(a) = q

Frequency(AA) = P
Frequency(Aa) = H
Frequency(aa) = Q

Mating	Frequency of Mating
AA x AA	P^2
AA x Aa	$2PH$
AA x aa	$2PQ$
Aa x Aa	H^2
Aa x aa	$2HQ$
aa x aa	Q^2

Hardy-Weinberg Principle

Frequency(A) = p
Frequency(a) = q

Frequency(AA) = P
Frequency(Aa) = H
Frequency(aa) = Q

		Frequency of progeny		
Mating	Frequency of Mating	AA	Aa	aa
AA x AA	P^2			
AA x Aa	$2PH$			
AA x aa	$2PQ$			
Aa x Aa	H^2			
Aa x aa	$2HQ$			
aa x aa	Q^2			

Hardy-Weinberg Principle

Frequency(A) = p
Frequency(a) = q

Frequency(AA) = P
Frequency(Aa) = H
Frequency(aa) = Q

Mating	Frequency of Mating	Frequency of progeny		
		AA	Aa	aa
AA x AA	P^2	1	0	0
AA x Aa	$2PH$			
AA x aa	$2PQ$			
Aa x Aa	H^2			
Aa x aa	$2HQ$			
aa x aa	Q^2			

Hardy-Weinberg Principle

Frequency(A) = p
Frequency(a) = q

Frequency(AA) = P
Frequency(Aa) = H
Frequency(aa) = Q

Mating	Frequency of Mating	Frequency of progeny		
		AA	Aa	aa
AA x AA	P^2	1	0	0
AA x Aa	$2PH$	1/2	1/2	0
AA x aa	$2PQ$			
Aa x Aa	H^2			
Aa x aa	$2HQ$			
aa x aa	Q^2			

Hardy-Weinberg Principle

Frequency(A) = p
Frequency(a) = q

Frequency(AA) = P
Frequency(Aa) = H
Frequency(aa) = Q

Mating	Frequency of Mating	Frequency of progeny AA	Aa	aa
AA x AA	P^2	1	0	0
AA x Aa	$2PH$	1/2	1/2	0
AA x aa	$2PQ$	0	1	0
Aa x Aa	H^2			
Aa x aa	$2HQ$			
aa x aa	Q^2			

Hardy-Weinberg Principle

Frequency(A) = p
Frequency(a) = q

Frequency(AA) = P
Frequency(Aa) = H
Frequency(aa) = Q

Mating	Frequency of Mating	Frequency of progeny AA	Frequency of progeny Aa	Frequency of progeny aa
AA x AA	P^2	1	0	0
AA x Aa	$2PH$	1/2	1/2	0
AA x aa	$2PQ$	0	1	0
Aa x Aa	H^2	1/4	1/2	1/4
Aa x aa	$2HQ$			
aa x aa	Q^2			

Hardy-Weinberg Principle

Frequency(A) = p
Frequency(a) = q

Frequency(AA) = P
Frequency(Aa) = H
Frequency(aa) = Q

Mating	Frequency of Mating	Frequency of progeny AA	Aa	aa
AA x AA	P^2	1	0	0
AA x Aa	$2PH$	1/2	1/2	0
AA x aa	$2PQ$	0	1	0
Aa x Aa	H^2	1/4	1/2	1/4
Aa x aa	$2HQ$	0	1/2	1/2
aa x aa	Q^2			

Hardy-Weinberg Principle

Frequency(A) = p
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Frequency(AA) = P
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Frequency(aa) = Q

Mating	Frequency of Mating	Frequency of progeny AA	Aa	aa
AA x AA	P^2	1	0	0
AA x Aa	$2PH$	1/2	1/2	0
AA x aa	$2PQ$	0	1	0
Aa x Aa	H^2	1/4	1/2	1/4
Aa x aa	$2HQ$	0	1/2	1/2
aa x aa	Q^2	0	0	1

Hardy-Weinberg Principle

Frequency(A) = p
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Frequency(AA) = P
Frequency(Aa) = H
Frequency(aa) = Q

		Frequency of progeny		
Mating	Frequency of Mating	AA	Aa	aa
AA x AA	P^2	$\boxed{1}$	0	0
AA x Aa	$2PH$	$\boxed{1/2}$	1/2	0
AA x aa	$2PQ$	$\boxed{0}$	1	0
Aa x Aa	H^2	$\boxed{1/4}$	1/2	1/4
Aa x aa	$2HQ$	$\boxed{0}$	1/2	1/2
aa x aa	Q^2	$\boxed{0}$	0	1

$P' =$

Hardy-Weinberg Principle

Frequency(A) = p
Frequency(a) = q

Frequency(AA) = P
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Frequency(aa) = Q

Mating	Frequency of Mating	Frequency of progeny AA	Aa	aa
AA x AA	P^2	1	0	0
AA x Aa	$2PH$	1/2	1/2	0
AA x aa	$2PQ$	0	1	0
Aa x Aa	H^2	1/4	1/2	1/4
Aa x aa	$2HQ$	0	1/2	1/2
aa x aa	Q^2	0	0	1

$$P' = P^2 + \frac{1}{2}2PH + \frac{1}{4}H^2$$

Hardy-Weinberg Principle

Frequency(A) = p
Frequency(a) = q

Frequency(AA) = P
Frequency(Aa) = H
Frequency(aa) = Q

Mating	Frequency of Mating	Frequency of progeny AA	Aa	aa
AA x AA	P^2	$\boxed{1}$	0	0
AA x Aa	$2PH$	1/2	1/2	0
AA x aa	$2PQ$	0	1	0
Aa x Aa	H^2	1/4	1/2	1/4
Aa x aa	$2HQ$	0	1/2	1/2
aa x aa	Q^2	0	0	1

$$P' = P^2 + \frac{1}{2}2PH + \frac{1}{4}H^2 = \left(P + \frac{H}{2}\right)^2$$

Hardy-Weinberg Principle

Frequency(A) = p
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Frequency(AA) = P
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Frequency(aa) = Q

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AA x AA	P^2	1	0	0
AA x Aa	$2PH$	1/2	1/2	0
AA x aa	$2PQ$	0	1	0
Aa x Aa	H^2	1/4	1/2	1/4
Aa x aa	$2HQ$	0	1/2	1/2
aa x aa	Q^2	0	0	1

$$P' = P^2 + \frac{1}{2}2PH + \frac{1}{4}H^2 = \left(P + \frac{H}{2}\right)^2 = p^2$$

Hardy-Weinberg Principle

Frequency(A) = p
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Mating	Frequency of Mating	AA	Aa	aa
AA x AA	P^2	1	0	0
AA x Aa	$2PH$	1/2	1/2	0
AA x aa	$2PQ$	0	1	0
Aa x Aa	H^2	1/4	1/2	1/4
Aa x aa	$2HQ$	0	1/2	1/2
aa x aa	Q^2	0	0	1

$$P' = P^2 + \frac{1}{2}2PH + \frac{1}{4}H^2 = \left(P + \frac{H}{2}\right)^2 = p^2$$

$$H' =$$

Hardy-Weinberg Principle

Frequency(A) = p
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		Frequency of progeny		
Mating	Frequency of Mating	AA	Aa	aa
AA x AA	P^2	1	0	0
AA x Aa	$2PH$	1/2	1/2	0
AA x aa	$2PQ$	0	1	0
Aa x Aa	H^2	1/4	1/2	1/4
Aa x aa	$2HQ$	0	1/2	1/2
aa x aa	Q^2	0	0	1

$$P' = P^2 + \frac{1}{2}2PH + \frac{1}{4}H^2 = \left(P + \frac{H}{2}\right)^2 = p^2$$

$$H' = \frac{1}{2}2PH + 2PQ + \frac{1}{2}H^2 + \frac{1}{2}2HQ$$

Hardy-Weinberg Principle

Frequency(A) = p
Frequency(a) = q

Frequency(AA) = P
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Frequency(aa) = Q

		Frequency of progeny		
Mating	Frequency of Mating	AA	Aa	aa
AA x AA	P^2	1	0	0
AA x Aa	$2PH$	1/2	1/2	0
AA x aa	$2PQ$	0	1	0
Aa x Aa	H^2	1/4	1/2	1/4
Aa x aa	$2HQ$	0	1/2	1/2
aa x aa	Q^2	0	0	1

$$P' = P^2 + \frac{1}{2}2PH + \frac{1}{4}H^2 = \left(P + \frac{H}{2}\right)^2 = p^2$$

$$H' = \frac{1}{2}2PH + 2PQ + \frac{1}{2}H^2 + \frac{1}{2}2HQ = 2(P + \frac{H}{2})(Q + \frac{H}{2})$$

Hardy-Weinberg Principle

Frequency(A) = p
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Frequency(AA) = P
Frequency(Aa) = H
Frequency(aa) = Q

Mating	Frequency of Mating	Frequency of progeny AA	Aa	aa
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AA x Aa	$2PH$	1/2	1/2	0
AA x aa	$2PQ$	0	1	0
Aa x Aa	H^2	1/4	1/2	1/4
Aa x aa	$2HQ$	0	1/2	1/2
aa x aa	Q^2	0	0	1

$$P' = P^2 + \frac{1}{2}2PH + \frac{1}{4}H^2 = \left(P + \frac{H}{2}\right)^2 = p^2$$

$$H' = \frac{1}{2}2PH + 2PQ + \frac{1}{2}H^2 + \frac{1}{2}2HQ = 2\left(P + \frac{H}{2}\right)\left(Q + \frac{H}{2}\right) = 2pq$$

Hardy-Weinberg Principle

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Mating	Frequency of Mating	Frequency of progeny AA	Aa	aa
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Aa x Aa	H^2	1/4	1/2	1/4
Aa x aa	$2HQ$	0	1/2	1/2
aa x aa	Q^2	0	0	1

$$P' = P^2 + \frac{1}{2}2PH + \frac{1}{4}H^2 = \left(P + \frac{H}{2}\right)^2 = p^2$$

$$H' = \frac{1}{2}2PH + 2PQ + \frac{1}{2}H^2 + \frac{1}{2}2HQ = 2\left(P + \frac{H}{2}\right)\left(Q + \frac{H}{2}\right) = 2pq$$

$$Q' =$$

Hardy-Weinberg Principle

Frequency(A) = p
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Frequency(AA) = P
Frequency(Aa) = H
Frequency(aa) = Q

Mating	Frequency of Mating	Frequency of progeny AA	Aa	aa
AA x AA	P^2	1	0	0
AA x Aa	$2PH$	1/2	1/2	0
AA x aa	$2PQ$	0	1	0
Aa x Aa	H^2	1/4	1/2	1/4
Aa x aa	$2HQ$	0	1/2	1/2
aa x aa	Q^2	0	0	1

$$P' = P^2 + \frac{1}{2}2PH + \frac{1}{4}H^2 = \left(P + \frac{H}{2}\right)^2 = p^2$$

$$H' = \frac{1}{2}2PH + 2PQ + \frac{1}{2}H^2 + \frac{1}{2}2HQ = 2\left(P + \frac{H}{2}\right)\left(Q + \frac{H}{2}\right) = 2pq$$

$$Q' = \frac{1}{4}H^2 + \frac{1}{2}2HQ + Q^2$$

Hardy-Weinberg Principle

Frequency(A) = p
Frequency(a) = q

Frequency(AA) = P
Frequency(Aa) = H
Frequency(aa) = Q

Mating	Frequency of Mating	Frequency of progeny AA	Aa	aa
AA x AA	P^2	1	0	0
AA x Aa	$2PH$	1/2	1/2	0
AA x aa	$2PQ$	0	1	0
Aa x Aa	H^2	1/4	1/2	1/4
Aa x aa	$2HQ$	0	1/2	1/2
aa x aa	Q^2	0	0	1

$$P' = P^2 + \frac{1}{2}2PH + \frac{1}{4}H^2 = \left(P + \frac{H}{2}\right)^2 = p^2$$

$$H' = \frac{1}{2}2PH + 2PQ + \frac{1}{2}H^2 + \frac{1}{2}2HQ = 2\left(P + \frac{H}{2}\right)\left(Q + \frac{H}{2}\right) = 2pq$$

$$Q' = \frac{1}{4}H^2 + \frac{1}{2}2HQ + Q^2 = \left(Q + \frac{H}{2}\right)^2$$

Hardy-Weinberg Principle

Frequency(A) = p
Frequency(a) = q

Frequency(AA) = P
Frequency(Aa) = H
Frequency(aa) = Q

Mating	Frequency of Mating	Frequency of progeny AA	Aa	aa
AA x AA	P^2	1	0	0
AA x Aa	$2PH$	1/2	1/2	0
AA x aa	$2PQ$	0	1	0
Aa x Aa	H^2	1/4	1/2	1/4
Aa x aa	$2HQ$	0	1/2	1/2
aa x aa	Q^2	0	0	1

$$P' = P^2 + \frac{1}{2}2PH + \frac{1}{4}H^2 = \left(P + \frac{H}{2}\right)^2 = p^2$$

$$H' = \frac{1}{2}2PH + 2PQ + \frac{1}{2}H^2 + \frac{1}{2}2HQ = 2(P + \frac{H}{2})(Q + \frac{H}{2}) = 2pq$$

$$Q' = \frac{1}{4}H^2 + \frac{1}{2}2HQ + Q^2 = \left(Q + \frac{H}{2}\right)^2 = q^2$$

Hardy-Weinberg Principle

$$P' = P^2 + \frac{1}{2}2PH + \frac{1}{4}H^2 = \left(P + \frac{H}{2}\right)^2 = p^2$$

$$H' = \frac{1}{2}2PH + 2PQ + \frac{1}{2}H^2 + \frac{1}{2}2HQ = 2(P + \frac{H}{2})(Q + \frac{H}{2}) = 2pq$$

$$Q' = \frac{1}{4}H^2 + \frac{1}{2}2HQ + Q^2 = \left(Q + \frac{H}{2}\right)^2 = q^2$$

Hardy-Weinberg Principle

$$P' = P^2 + \frac{1}{2}2PH + \frac{1}{4}H^2 = \left(P + \frac{H}{2}\right)^2 = p^2$$

$$H' = \frac{1}{2}2PH + 2PQ + \frac{1}{2}H^2 + \frac{1}{2}2HQ = 2(P + \frac{H}{2})(Q + \frac{H}{2}) = 2pq$$

$$Q' = \frac{1}{4}H^2 + \frac{1}{2}2HQ + Q^2 = \left(Q + \frac{H}{2}\right)^2 = q^2$$

$$p' =$$

Hardy-Weinberg Principle

$$P' = P^2 + \frac{1}{2}2PH + \frac{1}{4}H^2 = \left(P + \frac{H}{2}\right)^2 = p^2$$

$$H' = \frac{1}{2}2PH + 2PQ + \frac{1}{2}H^2 + \frac{1}{2}2HQ = 2(P + \frac{H}{2})(Q + \frac{H}{2}) = 2pq$$

$$Q' = \frac{1}{4}H^2 + \frac{1}{2}2HQ + Q^2 = \left(Q + \frac{H}{2}\right)^2 = q^2$$

$$p' = P' + \frac{1}{2}H'$$

Hardy-Weinberg Principle

$$P' = P^2 + \frac{1}{2}2PH + \frac{1}{4}H^2 = \left(P + \frac{H}{2}\right)^2 = p^2$$

$$H' = \frac{1}{2}2PH + 2PQ + \frac{1}{2}H^2 + \frac{1}{2}2HQ = 2(P + \frac{H}{2})(Q + \frac{H}{2}) = 2pq$$

$$Q' = \frac{1}{4}H^2 + \frac{1}{2}2HQ + Q^2 = \left(Q + \frac{H}{2}\right)^2 = q^2$$

$$p' = P' + \frac{1}{2}H' = p^2 + \frac{1}{2}2pq$$

Hardy-Weinberg Principle

$$P' = P^2 + \frac{1}{2}2PH + \frac{1}{4}H^2 = \left(P + \frac{H}{2}\right)^2 = p^2$$

$$H' = \frac{1}{2}2PH + 2PQ + \frac{1}{2}H^2 + \frac{1}{2}2HQ = 2(P + \frac{H}{2})(Q + \frac{H}{2}) = 2pq$$

$$Q' = \frac{1}{4}H^2 + \frac{1}{2}2HQ + Q^2 = \left(Q + \frac{H}{2}\right)^2 = q^2$$

$$p' = P' + \frac{1}{2}H' = p^2 + \frac{1}{2}2pq = p(p + q)$$

Hardy-Weinberg Principle

$$P' = P^2 + \frac{1}{2}2PH + \frac{1}{4}H^2 = \left(P + \frac{H}{2}\right)^2 = p^2$$

$$H' = \frac{1}{2}2PH + 2PQ + \frac{1}{2}H^2 + \frac{1}{2}2HQ = 2(P + \frac{H}{2})(Q + \frac{H}{2}) = 2pq$$

$$Q' = \frac{1}{4}H^2 + \frac{1}{2}2HQ + Q^2 = \left(Q + \frac{H}{2}\right)^2 = q^2$$

$$p' = P' + \frac{1}{2}H' = p^2 + \frac{1}{2}2pq = p(p+q) = p$$

$$q' = Q' + \frac{1}{2}H' = q^2 + \frac{1}{2}2pq = q(q+p) = q$$

- Allele frequency unchanged across generations
  - Mendelian inheritance itself preserves variation
- HWE achieved in ONE generation
  - Equal allele frequencies in males & females, discrete generations