

# Association testing I

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$ echo "Data Sciences Institute"
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# What You'll Learn Today

- Set up the regression models or table-based tests and choose appropriate genotype codings.
- Interpret effect sizes, uncertainty, and evidence to make clear claims about variant–trait links.
- Recognize key assumptions, power drivers, and the role of LD so you can judge how much to trust a finding.

# Association Testing

- **Objective:** establish association between a trait of interest and a genetic marker.
- Study designs: case-control, case-cohort, population-based design.
- Unrelated subjects or **population-based designs:** easy to collect so possible to achieve large sample sizes as in GWAS.
- **Family-based designs:** robust to population stratification, more difficult to collect.  
Also hard to collect for late-onset diseases.

# Overview

- For a quantitative trait  $Y$ : simple linear regression models to detect association between  $Y$  and  $G$ :

$$Y = \alpha + \beta G + e, e \sim N(0, \sigma^2).$$

- Coding of  $G$ : 1 d.f. additive (or dominant, recessive) model or 2 d.f. genotypic model.

$G =$	aa	Aa	AA
Additive	0	1	2
Dominant	0	1	1
Recessive	0	0	1
Genotypic	"0"	"1"	"2"

# Overview

- **1 d.f. model:**  $Y = \alpha + \beta G + e, e \sim N(0, \sigma^2)$ .
  - The test of no association is equivalent to  $H_0 : \beta = 0$ .
- **Genotypic (2 d.f.) model:**  $Y = \alpha + \beta_1 D_1 + \beta_2 D_2 + e, e \sim N(0, \sigma^2)$ .
  - $D_1 = I(G = Aa), D_2 = I(G = AA)$ .
  - $H_0 : \beta_1 = \beta_2 = 0$ .
- **Extended model** (includes environment, other SNPs, interactions):
$$Y = \alpha + \beta G + \gamma E + \delta GxE + e, e \sim N(0, \sigma^2).$$

# Association Analysis for Binary Trait

- For a binary trait  $Y$ :  $Y = 1$  denotes for being affected/cases, and  $Y = 0$  for unaffected/controls
- SNP: categorical variable with three genotypes (Aa, aa and AA)
- Genotype frequency differ between cases and controls only at the DSL or markers that are in LD with the DSL
- How do we detect association between  $Y$  and  $G$  ?
  - **Compare frequency differences between cases and controls**
  - **Use regression framework** to unify analysis (QTL + binary traits, with covariates and interactions)

# Association Testing (2 df test)

- Observed genotype counts at a marker under the study for  $r$  cases and  $s$  controls.

	aa	Aa	AA	Total
Cases	$r_0$	$r_1$	$r_2$	$r$
Controls	$s_0$	$s_1$	$s_2$	$s$
Total	$n_0$	$n_1$	$n_2$	$n$

- Most general test: nothing is assumed about the relationship between disease and genotype.

$$H_0 : P(Y = 1 \mid AA) = P(Y = 1 \mid Aa) = P(Y = 1 \mid aa)$$

$H_A$  : At least one inequality holds

# Contingency Table - Pearson's Homogeneity Test

- Assume we have independent observations from  $I$  multinomial distributions, each of which has  $J$  categories, e.g.  $I = 2$ .

	$X = 0$	$X = 1$	$\dots$	$X = J - 1$	Total
Cases	$r_0$	$r_1$	$\dots$	$r_{J-1}$	$r$
Controls	$s_0$	$s_1$	$\dots$	$s_{J-1}$	$s$
Total	$n_0$	$n_1$	$\dots$	$n_{J-1}$	$n$

- Our goal is to test whether the multinomial distributions for the two groups are identical.

$$H_0 : \pi_{1j} = \pi_{2j} \equiv \pi_j, \quad j = 0, 1, \dots, J - 2.$$

# Pearson's Homogeneity Test

- Test Statistic

$$T = \sum \frac{(O - E)^2}{E} \sim \chi^2_{(I-1)(J-1)}.$$

- E: expected counts under the null hypothesis of homogeneity using pooled estimate  
 $\tilde{\pi}_j = \frac{n_j}{n}.$
- df =  $(I - 1)(J - 1)$ : number of independent counts ( $I(J - 1)$ ) - the number of independent parameters estimated under the null from the data ( $J - 1$ ).

# Association Testing (2 df test)

- |          | aa    | Aa    | AA    | Total |
|----------|-------|-------|-------|-------|
| Cases    | $r_0$ | $r_1$ | $r_2$ | $r$   |
| Controls | $s_0$ | $s_1$ | $s_2$ | $s$   |
| Total    | $n_0$ | $n_1$ | $n_2$ | $n$   |

- Two df Pearson test of independence:

$$\chi^2 = \sum (O - E)^2 / E.$$

- Sum is over all six entries. e.g.  $E[\text{Case \& aa}] = (r \cdot n_0) / n$ .

# Association Testing (1 df test)

- For example:

	aa	Aa	Total
Cases	$r_0$	$r_1$	$r$
Controls	$s_0$	$s_1$	$s$
Total	$n_0$	$n_1$	$n$

$$T = \frac{\left(r_0 - \frac{rn_0}{n}\right)^2}{\frac{rn_0}{n}} + \frac{\left(r_1 - \frac{rn_1}{n}\right)^2}{\frac{rn_1}{n}} + \frac{\left(s_0 - \frac{sn_0}{n}\right)^2}{\frac{sn_0}{n}} + \frac{\left(s_1 - \frac{sn_1}{n}\right)^2}{\frac{sn_1}{n}} \sim \chi^2_1.$$

# Association Testing - Dominant model

- |          | aa    | Aa or AA    | Total |
|----------|-------|-------------|-------|
| Cases    | $r_0$ | $r_1 + r_2$ | $r$   |
| Controls | $s_0$ | $s_1 + s_2$ | $s$   |
| Total    | $n_0$ | $n_1 + n_2$ | $n$   |

- Dominant model:

$$H_0 : P(Y = 1 \mid AA) = P(Y = 1 \mid Aa) = P(Y = 1 \mid aa)$$
$$H_A : P(Y = 1 \mid AA \text{ or } Aa) \neq P(Y = 1 \mid aa)$$

- Replace  $r_1$  with  $r_1 + r_2$  with 1 df chi-square test.
- Optimal when the true disease model is dominant but not for recessive.

# Exercise

- Recessive model:

	<b>aa or Aa</b>	<b>AA</b>	<b>Total</b>
Cases	$r_0 + r_1$	$r_2$	$r$
Controls	$s_0 + s_1$	$s_2$	$s$
Total	$n_0 + n_1$	$n_2$	$n$

# Association Testing - Additive Model

- We can also test for association using **allele counts**.
- $H_0 : p_{cases} = p_{controls}$

	a	A	Total
Cases	$2r_0 + r_1$	$r_1 + 2r_2$	$2r$
Controls	$2s_0 + s_1$	$s_1 + s_2$	$2s$
Total	$n_a$	$n_A$	$2n$

- Assumptions: samples are independent both within each group (cases and controls) and between groups. Under this assumption, allele count data can be modeled using two independent binomial distributions.

## Estimating Effect Sizes - Risk Ratio (RR)

- A natural measure of effect size is relative risk ratio:  $RR = \frac{P(\text{ disease } | \text{ exposed })}{P(\text{ disease } | \text{ unexposed })}$ .
- Exposure = genotype; recessive model: AA vs (Aa, aa).
- In case-control or genotype-ascertained samples, group risks are distorted.
- Therefore RR cannot be validly estimated from those designs.

# Odds Ratio

- Odds Ratio are used to approximate the relative risk (RR) for case-control or case-cohort sampling.
- OR compares odds:  $\frac{P(D|E)/(1-P(D|E))}{P(D|\bar{E})/(1-P(D|\bar{E}))}$ .

- |           | Disease (+) | Disease (-) | Total |
|-----------|-------------|-------------|-------|
| Exposed   | a           | b           | a+b   |
| Unexposed | c           | d           | c+d   |

$$OR = \frac{a/c}{b/d} = \frac{ad}{bc}.$$

- When the outcome is rare,  $OR \approx RR$ .

## Inference of ORs

- $OR = \frac{a/c}{b/d} = \frac{ad}{bc}$ .
- Log(OR) approximately normal.
- Variance:

$$\text{Var}[\log(OR)] \approx \frac{1}{a} + \frac{1}{b} + \frac{1}{c} + \frac{1}{d}.$$

- 95% CI:

$$\exp \left( \log(OR) \pm 1.96 \cdot \sqrt{\text{Var}[\log(OR)]} \right).$$

## Limitations of Previous Tests

- Work well only for simple binary traits without major environmental influence
- Do not easily adjust for covariates (e.g., age, sex, ancestry)
- Population stratification can confound results if unadjusted
- Stratified analyses are one workaround, but not always sufficient

# Properties of OR

- Let  $\pi_1^* = P(\text{ case } | Aa)$  and  $\pi_2^* = P(\text{ case } | aa)$ .
- Let  $\pi_1 = P(Aa | \text{ case})$  and  $\pi_2 = P(Aa | \text{ control})$ .
- We have the following result that links the two quantities:

$$\begin{aligned}\frac{\text{odds}(\text{ case } | Aa)}{\text{odds}(\text{ case } | aa)} &= \frac{\pi_1^*}{1 - \pi_1^*} / \frac{\pi_2^*}{1 - \pi_2^*} \\ &= \frac{\pi_1}{1 - \pi_1} / \frac{\pi_2}{1 - \pi_2} = \frac{\text{odds}(Aa | \text{ case})}{\text{odds}(Aa | \text{ control})}.\end{aligned}$$

## Details of the derivation

$$\begin{aligned} \frac{\text{odds}(\text{ case } | Aa)}{\text{odds}(\text{ case } | aa)} &= \frac{\pi_1^*}{1 - \pi_1^*} / \frac{\pi_2^*}{1 - \pi_2^*} = \frac{P(\text{ case } | Aa)}{1 - P(\text{ case } | Aa)} / \frac{P(\text{ case } | aa)}{1 - P(\text{ case } | aa)} \\ &= \frac{P(\text{ case } | Aa)}{P(\text{ control } | Aa)} / \frac{P(\text{ case } | aa)}{P(\text{ control } | aa)} = \frac{P(\text{ case}, Aa)P(Aa)}{P(\text{ control}, Aa)P(Aa)} / \frac{P(\text{ case}, aa)P(aa)}{P(\text{ control}, aa)P(aa)} \\ &\quad = \frac{P(\text{ case}, Aa)}{P(\text{ control}, Aa)} / \frac{P(\text{ case}, aa)}{P(\text{ control}, aa)} \\ &= \frac{P(Aa | \text{ case})P(\text{ case})}{P(Aa | \text{ control})P(\text{ control})} / \frac{P(aa | \text{ case})P(\text{ case})}{P(aa | \text{ control})P(\text{ control})} \\ &\quad = \frac{P(Aa | \text{ case})}{P(aa | \text{ case})} / \frac{P(Aa | \text{ control})}{P(aa | \text{ control})} \\ &= \frac{P(Aa | \text{ case})}{1 - P(Aa | \text{ case})} / \frac{P(Aa | \text{ control})}{1 - P(aa | \text{ control})} = \frac{\pi_1}{1 - \pi_1} / \frac{\pi_2}{1 - \pi_2} = \frac{\text{odds}(Aa | \text{ case})}{\text{odds}(Aa | \text{ control})} \end{aligned}$$

# Regression Framework: Extending to Covariates & Traits

- Use Generalized Linear Models (GLMs):

$$g(E[Y | X]) = \alpha + X\beta$$

- Link function  $g$  depends on trait type:
- Binary traits (logistic):

$$\log \frac{E[Y | X]}{1 - E[Y | X]} = \alpha + X\beta$$

- Continuous traits (linear):

$$E[Y | X] = b_0 + Xb_1$$

- $X$  = coded genotype (additive, dominant, recessive, etc.)

# Regression Framework

- Tests genetic effect:

$$H_0 : b_1 = 0$$

- Inference via likelihood ratio test, Wald test, or score test
- Key advantage: allows easy adjustment for covariates (age, sex, ancestry, etc.)
- Flexible framework for analyzing both binary and continuous traits

## Remarks

- For logistic regression, the **estimated coefficient  $\beta$**  is equal to the  $\log(\text{OR})$  (for the corresponding model)
- For continuous outcomes, the coefficient  $\beta$  represents differences in means by genotype group
  - For recessive model,  $\beta$  is the mean phenotype for the AA group - mean phenotype for Aa or aa group
  - For the additive model,  $b_1$  is the mean increase in phenotype with each additional allele.

# Interpretation of Logistic Regression

- Consider logit of  $\mu$  as a linear function of  $X$ .

$$\mu(X) = E(Y | X) = P(Y = 1 | X)$$

$$\text{logit}(P(Y = 1 | X)) = \text{logit}(\mu(X)) = \log \frac{\mu(X)}{1 - \mu(X)} = \alpha + \beta X$$

$$\implies P(Y = 1 | X) = \frac{\exp(\alpha + \beta X)}{1 + \exp(\alpha + \beta X)},$$

$$P(Y = 0 | X) = \frac{1}{1 + \exp(\alpha + \beta X)}.$$

# Interpretation of Logistic Regression

- What is the interpretation of the parameters,  $\alpha$  and  $\beta$  ?

$$\text{logit}(\mu(X)) = \log \frac{\mu(X)}{1 - \mu(X)} = \alpha + \beta X.$$

- For individuals carry genotype aa,  $X = 0$  :

$$\text{logit}(\mu(X = 0)) = \alpha.$$

- Thus,

$$\alpha = \text{logit}(\mu(X = 0)) = \log \left( \frac{\mu(X = 0)}{1 - \mu(X = 0)} \right) = \log \left( \frac{P(Y = 1 | aa)}{1 - P(Y = 1 | aa)} \right)$$

is the log-odds of being affected/case for genotype aa.

# Interpretation of Logistic Regression

- For individuals carry genotype Aa,  $X = 1$  :

$$\text{logit}(\mu(X = 1)) = \alpha + \beta.$$

- Thus,

$$\begin{aligned}\beta &= \text{logit}(\mu(X = 1)) - \text{logit}(\mu(X = 0)) = \log\left(\frac{\mu(X = 1)}{1 - \mu(X = 1)}\right) - \log\left(\frac{\mu(X = 0)}{1 - \mu(X = 0)}\right) \\ &= \log\left(\frac{P(Y = 1 | Aa)}{1 - P(Y = 1 | Aa)}\right) - \log\left(\frac{P(Y = 1 | aa)}{1 - P(Y = 1 | aa)}\right) = \log\left(\frac{\pi_1^*}{1 - \pi_1^*}\right) - \log\left(\frac{\pi_2^*}{1 - \pi_2^*}\right) \\ &= \log\left(\frac{P(Aa | Y = 1)}{1 - P(Aa | Y = 1)}\right) - \log\left(\frac{P(Aa | Y = 0)}{1 - P(Aa | Y = 0)}\right) = \log\left(\frac{\pi_1}{1 - \pi_1}\right) - \log\left(\frac{\pi_2}{1 - \pi_2}\right).\end{aligned}$$

# Interpretation of Logistic Regression

- $\beta$  is the log-odds ratio of being affected/case for individuals with genotype Aa ( $X = 1$  copy of allele A) compared with being affected/case for individuals with genotype aa ( $X = 0$  copies of allele A)
- $\beta$  also equals to the log-odds ratio of having genotype Aa among cases compared with having genotype Aa among controls.

# Logistic Regression Likelihood

- Probability of outcome:

$$P(Y_i = 1 \mid X_i = x_i) = \frac{\exp(\alpha + \beta x_i)}{1 + \exp(\alpha + \beta x_i)},$$

$$P(Y_i = 0 \mid X_i = x_i) = \frac{1}{1 + \exp(\alpha + \beta x_i)}.$$

- Compact form (for  $y_i = 0$  or  $1$ ):

$$P(Y_i = y_i \mid X_i = x_i) = \frac{\exp((\alpha + \beta x_i)y_i)}{1 + \exp(\alpha + \beta x_i)}.$$

- Assuming independence:

$$P(Y_1 = y_1, \dots, Y_n = y_n \mid X_1 = x_1, \dots, X_n = x_n) = \prod_{i=1}^n P(Y_i = y_i \mid X_i = x_i). \quad 28$$

# Logistic Regression Likelihood

- Likelihood function:

$$L(\alpha, \beta) = \prod_{i=1}^n \frac{\exp((\alpha + \beta x_i)y_i)}{1 + \exp(\alpha + \beta x_i)}.$$

- Log-likelihood:

$$l(\alpha, \beta) = \sum_{i=1}^n [(\alpha + \beta x_i)y_i - \log(1 + \exp(\alpha + \beta x_i))].$$

- Estimation:

- Parameters  $\alpha, \beta$  obtained by Maximum Likelihood Estimation (MLE)
- No closed-form solution → need iterative methods (Newton-Raphson, Fisher scoring, etc.)

# Logistic Regression Likelihood (More Advanced)

- |          | aa    | Aa    | Total |
|----------|-------|-------|-------|
| Cases    | $r_0$ | $r_1$ | $r$   |
| Controls | $s_0$ | $s_1$ | $s$   |
| Total    | $n_0$ | $n_1$ | $n$   |

- Results for  $\beta$  are identical to the ones derived from a  $2 \times 2$  table for log OR.

$$\hat{\alpha} = \log\left(\frac{r_0}{s_0}\right), SE(\hat{\alpha}) = \sqrt{\frac{1}{r_0} + \frac{1}{s_0}},$$

$$\hat{\beta} = \log\left(\frac{r_1 s_0}{r_0 s_1}\right), SE(\hat{\beta}) = \sqrt{\frac{1}{r_0} + \frac{1}{r_1} + \frac{1}{s_0} + \frac{1}{s_1}}.$$

## MLE Derivation Details (More Advanced)

- Note that  $r_0 : Y = 1, X = 0, r_1 : Y = 1, X = 1, s_0 : Y = 0, X = 0, s_1 : Y = 0, X = 1$ . We can simplify the log likelihood:

$$\begin{aligned} I(\theta) &= I(\alpha, \beta) = \sum_{i=1}^n \log \left( \frac{\exp((\alpha + \beta x_i) \cdot y_i)}{1 + \exp(\alpha + \beta x_i)} \right) \\ &= r_0 \cdot \log \left( \frac{\exp(\alpha)}{1 + \exp(\alpha)} \right) + r_1 \cdot \log \left( \frac{\exp(\alpha + \beta)}{1 + \exp(\alpha + \beta)} \right) \\ &\quad + s_0 \log \left( \frac{1}{1 + \exp(\alpha)} \right) + s_1 \cdot \log \left( \frac{1}{1 + \exp(\alpha + \beta)} \right) \\ &= r_0 \alpha - r_0 \log(1 + \exp(\alpha)) + r_1 (\alpha + \beta) - r_1 \log(1 + \exp(\alpha + \beta)) \\ &\quad - s_0 \log(1 + \exp(\alpha)) - s_1 \log(1 + \exp(\alpha + \beta)) \\ &= r\alpha + r_1\beta - n_0 \log(1 + \exp(\alpha)) - n_1 \log(1 + \exp(\alpha + \beta)). \end{aligned}$$

## MLE Derivation Details (More Advanced)

- Obtain the score functions

$$\frac{\partial I(\theta)}{\partial \alpha} = r - n_0 \frac{\exp(\alpha)}{1 + \exp(\alpha)} - n_1 \frac{\exp(\alpha + \beta)}{1 + \exp(\alpha + \beta)}$$

$$\frac{\partial I(\theta)}{\partial \beta} = r_1 - n_1 \frac{\exp(\alpha + \beta)}{1 + \exp(\alpha + \beta)}.$$

# MLE Derivation Details (More Advanced)

- Calculate the MLE

$$\frac{\partial I(\theta)}{\partial \alpha} = 0, \frac{\partial I(\theta)}{\partial \beta} = 0 \implies$$

$$r - n_0 \frac{\exp(\hat{\alpha})}{1 + \exp(\hat{\alpha})} - r_1 = 0 \implies \exp(\hat{\alpha}) = \frac{r_0}{s_0} \implies \hat{\alpha} = \log \frac{r_0}{s_0}$$

$$\frac{\exp(\hat{\alpha} + \hat{\beta})}{1 + \exp(\hat{\alpha} + \hat{\beta})} = \frac{r_1}{n_1} \implies \exp(\hat{\alpha} + \hat{\beta}) = \exp(\hat{\alpha}) \cdot \exp(\hat{\beta}) = \frac{r_1}{n_1 - r_1} = \frac{r_1}{s_1}$$
$$\implies \exp(\hat{\beta}) = \frac{r_1}{s_1} / \frac{r_0}{s_0} = \frac{r_1 s_0}{r_0 s_1} \implies \hat{\beta} = \log \frac{r_1 s_0}{r_0 s_1}.$$

- Variance calculation involves the second derivatives and the Fisher's information.

# Logistic Regression Inference

- How would we perform a formal hypothesis test of

$$H_0 : \beta = 0$$

- Wald test would be identical to the test derived for testing  $\Delta = 0$

$$T = \left( \frac{\hat{\beta} - 0}{SE(\hat{\beta})} \right)^2 \sim \chi^2_1.$$

$$\hat{\beta} = \log \left( \frac{r_1 s_0}{r_0 s_1} \right),$$

$$SE(\hat{\beta}) = \sqrt{\frac{1}{r_0} + \frac{1}{r_1} + \frac{1}{s_0} + \frac{1}{s_1}}.$$

# Logistic Regression Inference

- LRT

$$T = 2 \left( \log \left( L_{H_1}(\hat{\alpha}, \hat{\beta}) \right) - \log \left( L_{H_0}(\tilde{\alpha}, \beta = 0) \right) \right) \sim \chi^2_1.$$

- $\tilde{\alpha} = ?$

$$\begin{aligned} H_0 : \beta &= 0, \\ \log \left( \frac{\mu(X)}{1 - \mu(X)} \right) &= \alpha. \end{aligned}$$

$$L(\theta) = L(\alpha, 0) = \prod_{i=1}^n \frac{\exp((\alpha) \cdot y_i)}{1 + \exp(\alpha)}$$

# Logistic Regression Inference

$$\begin{aligned} I(\theta) &= I(\alpha, 0) = \sum_{i=1}^n \log \left( \frac{\exp((\alpha) \cdot y_i)}{1 + \exp(\alpha)} \right) \\ &= r \cdot \log \left( \frac{\exp(\alpha)}{1 + \exp(\alpha)} \right) + s \cdot \log \left( \frac{1}{1 + \exp(\alpha)} \right) \\ &= r \cdot \alpha - n \cdot \log(1 + \exp(\alpha)) \\ \frac{\partial I(\theta)}{\partial \alpha} &= r - n \cdot \frac{\exp(\alpha)}{1 + \exp(\alpha)} \\ \frac{\partial I(\theta)}{\partial \alpha} = 0 &\implies \tilde{\alpha} = \log \frac{r/n}{(n-r)/n} = \log \frac{\mu}{1-\mu} \end{aligned}$$

- This is not surprising since  $r/n$  is a pooled estimate of  $\mu = P(Y = 1)$  regardless of the value of  $X$ .

# Logistic Regression Inference

- Score test involves the score function and the Fisher's information evaluated under the null hypothesis that  $\beta = 0$ .

$$T = S(\tilde{\alpha}, \beta = 0)' I(\tilde{\alpha}, \beta = 0)^{-1} S(\tilde{\alpha}, \beta = 0) \sim \chi_1^2.$$

- Note that the CI for OR is derived from the CI for log OR, e.g. 95%CI for OR is

$$(\exp(\hat{\beta} - 1.96SE(\hat{\beta})), (\exp(\hat{\beta} + 1.96SE(\hat{\beta})))$$

# Exercise

- The data below come from the study by Knowler et al. (1988), on the association between IDDM type 2 and a haplotype from the GM system human immunoglobulin *G*. These data include all individuals in a sample of 4,920 Native Americans of the Pima and Papago tribes. In this example, think of the GM haplotype as just an allele at a suspected DSL.

GM haplotype	# subjects	#(%) with IDDM
Present	293	23(7.9)
Absent	4627	1343(29.0)

# Exercise

- We can reformulate the data:

GM haplotype	affected/case (%)	unaffected/control	Total
Present, D	23(7.9)	270	293
Absent, d	1343(29.0)	3284	4627
Total	1366	3554	4920

- We are interested in comparing 7.9% with 29%.

# Power and Significance

- Power  $1 - \beta$ : probability of detecting an effect when it truly exists.
- Significance level  $\alpha$  : probability of false positive (rejecting  $H_0$  when true)

- | Effect | Detect      | Not Detect   |
|--------|-------------|--------------|
| True   | $1 - \beta$ | $\beta$      |
| False  | $\alpha$    | $1 - \alpha$ |

- Goal: minimize  $\alpha$  and maximize  $1 - \beta$ .

# Power Estimation

- Many genetic association tests follow a normal or chi-squared distribution
- Under  $H_1$  : distribution becomes noncentral chi-squared with noncentrality parameter (NCP)  $\lambda$
- For a test statistic  $T$  :
  - $H_0 : E(T) = df$  ( central  $\chi^2$ )
  - $H_1 : E(T) = df + NCP$  ( noncentral  $\chi^2$ )

# How to Increase Power

- Example (allelic test at a SNP): true effect size  $a = \log(OR)$ , risk allele frequency  $f$  and proportion of cases  $\phi = r/n$ .
- The noncentrality parameter:

$$NCP \approx 2\phi(1 - \phi)na^2f(1 - f)$$

- Increase sample size  $n$
- Increase effect size  $a$  (e.g., extreme case selection)
- Adjust case/control ratio  $\phi$

# Linkage Disequilibrium (LD)

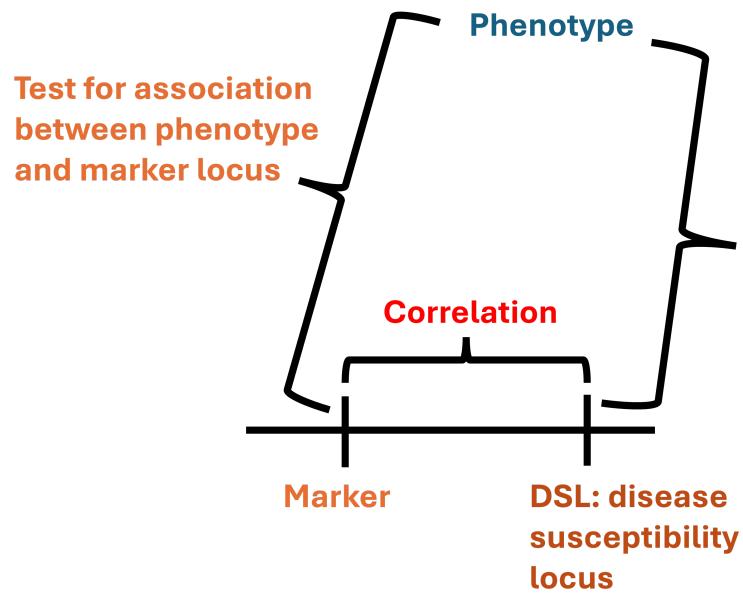
- LD is commonly measured using the Pearson correlation ( $\rho$ ) between genotypes at two markers



Source: Publicly available from Google Images

# Indirect Association

- We usually test genetic markers, not the actual causal mutation
- A marker may be correlated with the true disease-causing variant → indirect association
- Linkage disequilibrium (LD) between a marker and the causal variant creates an observed association with the phenotype



# International HapMap Project

- Multinational project launched at the end of the Human Genome Project
- **Main goal:** provide data to estimate **linkage disequilibrium (LD)** across populations
- DNA samples collected from 4 groups:
  - 30 Yoruba trios (Nigeria)
  - 30 CEPH trios (European ancestry)
  - 45 Japanese (Tokyo)
  - 45 Han Chinese (Beijing)

# International HapMap Project

- Data: SNP genotypes for 270 individuals + allele frequencies in each population
- Provides standard LD measures (e.g.,  $\rho^2$ )
- Impact: reduced the number of SNPs needed for GWAS
  - From ~10 million SNPs → ~500,000 tag SNPs

# SNP Microarrays

- SNP: single nucleotide polymorphism (usually biallelic: A/a)
- SNP arrays detect common variants ( $\geq 5\%$  frequency) in a population
- Nearby SNPs are correlated → ~300K–600K tag SNPs capture most variation
- Modern platforms cover >1 million SNPs to map common variation

## LD Varies by Population

- LD patterns differ across populations
- Example:
  - [LDlink tool](#)
  - SNP pair: *rs146366639* and *rs6661489*

# What's Next

- Population substructure in association studies
- Association analysis in family designs

**What questions do you have about anything from today?**

