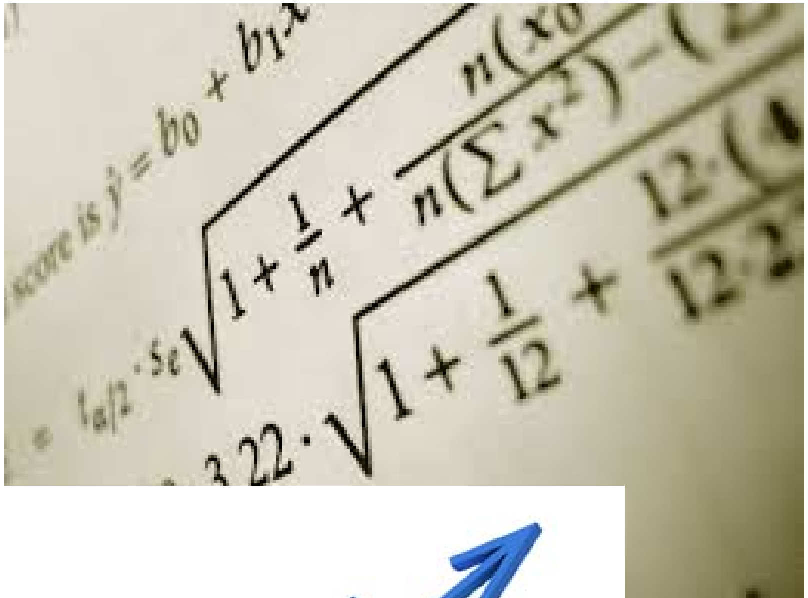
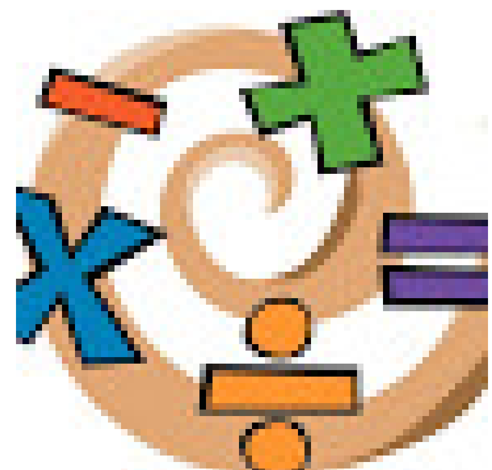
Analysis of Variance





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Objectives

↓

Statistical hypotheses

↓

Statistical tests

(to prove the hypotheses as true or false)

Statistical hypotheses

Null hypothesis (Ho) states that there are no differences among treatment means

-- **Objective is to reject Ho so that we can conclude that differences exist among treatments.**

Alternative hypothesis (Ha) states the opposite of Ho

Example

Objective: To compare the shelf life (sl) in days of 4 chili pepper varieties (V1, V2, V3, V4)

<u>Null hypothesis</u>

Ho: $sl_1 = sl_2 = sl_3 = sl_4$

<u>Alternative hypothesis</u>

Ha: $sl_1 \neq sl_2 \neq sl_3 \neq sl_4$

Example

Objective: To compare the firmness of tomato fruits with and without packaging

Null hypothesis Ho: with p = w/out p

Alternative hypothesis Ha: with p $\neq$ w/out p

Example

Objective: To assess the effect of 2 irrigation types (drip, furrow) on fruit weight (fwt) of chili pepper

Null hypothesis Ho: fwtdrip = fwtfurrow

Alternative hypothesis Ha: fwtdrip ≠ fwtfurrow

Test of significance

<u>Objective</u> is to reject 'Ho' so that it can be concluded that significant differences exist among treatments.

F = TrMS/EMS

- If F-test is significant, reject Ho and accept Ha.
- If F-test is nonsignificant, we do not accept Ho, rather, we say that the test failed to detect significant differences

Concept of Analysis of Variance

Completely Randomized Design (CRD)

5 tomato varieties (V1, V2,….V5), 2 replications

Experimental unit = one plot, each measuring 3m x 4m. Yield is measured on each plot

Y1 V1	Y2 V4	Y3 V1	Y4 V3	Y5 V4
Y6 V2	Y7 V3	Y8 V5	Y9 V2	Y10 V5

Y1, Y2, Y3, Y4, Y5, Y6, Y7, Y8, Y9, Y10 = plot yields

Concept of Analysis of Variance

Case 1

4 V1	4 V4	4 V1	4 V3	4 V4
4 V2	4 V3	4 V5	4 V2	4 V5

$Y_1 = Y_2 = Y_3 = Y_4 = Y_5 = Y_6 = Y_7 = Y_8 = Y_9 = Y_{10}$ = **‘4’**

Mean = 4 Variance = 0 **(no variation)**

Concept of Analysis of Variance

Case 2

2 V1	3 V4	4 V1	1 V3	3 V4
5 V2	3 V3	6 V5	4 V2	2 V5

Y_1=***2***, Y_2=***3***, Y_3=***4***, Y_4=***1***, Y_5=***3***,
Y_6 =*5*, Y_7 =***3***, Y_8 = ***6***, Y_9 = ***4***, Y_{10} =***2***

Mean = 3.3 Variance = 2.2

Concept of Analysis of Variance

The total variation (*variance=2.2*) among these 10 quantities is called the ***total sum of squares (TSS)*** and can be computed through the analysis of variance (ANOVA).

Measures of Central Tendency

Describe the middle or center of distribution

10 observations → 6 5 4 4 3 3 3 2 2 1

- **Mean** – sum of the observations divided by the number of observations

  (6+5+4+4+3+3+3+2+2+1) ÷ 10 = **3.3**

- **Median** – number where half of the observations are above and half are below it.

  6 5 4 4 3 3 3 2 2 1 = (3+3) ÷ 2 = **3**

- **Mode** – value that occurs most frequently = **3**

Measures of Dispersion

Describe how data spreads out or cluster around the middle or center of distribution

- Variance or standard deviation
- Range

Sample mean and variance

40	40
40	40
40	40
40	40
40	40
40	40

$$\text{Mean} = \frac{\sum X_i}{n}$$

$$= \frac{40 + 40 + \ldots\ldots + 40}{12} = 40$$

$$\text{Var} = \frac{\sum (X_i - \overline{X})^2}{n-1}$$

$$= \frac{(40-40)^2 + \ldots\ldots + (40-40)^2}{11} = 0$$

$$\text{Standard error of the mean (Sem)} = \sqrt{\frac{\text{var}}{n}} = \sqrt{\frac{0}{12}} = 0$$

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Sample mean and variance

36	40
36	40
36	40
36	40
36	40
36	40

Mean = $\frac{\sum X_i}{n}$

= $\frac{36 + 36 + ... + 40}{12}$ **= 38**

Var = $\frac{\sum (X_i - \overline{X})^2}{n-1}$

= $\frac{(36-38)^2 + (40-38)^2 ...... + (40-38)^2}{11}$ **= 4.36**

Sem = $\sqrt{\frac{\text{var}}{\text{n}}} = \sqrt{\frac{4.36}{12}}$ **= 0.60**

$\mu = \overline{\text{X}} \pm \text{Sem}$ = 38 ±0.60 = (37.4, 38.60)

Sample mean and variance

35	47
38	40
36	49
30	38
39	42
34	41

$$\text{Mean} = \frac{\sum X_i}{n}$$

$$= \frac{35 + 38 + \ldots\ldots + 42 + 41}{12} = \mathbf{39.1}$$

$$\text{Var} = \frac{\sum (X_i - \overline{X})^2}{n-1}$$

$$= \frac{(35 - 39.1)^2 + (38 - 39.1)^2 \ldots\ldots + (41 - 39.1)^2}{11} = \mathbf{28.3}$$

$$\text{Sem} = \sqrt{\frac{\text{var}}{\text{n}}} = \sqrt{\frac{28.3}{12}} = \mathbf{1.54}$$

$$\mu = \overline{\mathrm{X}} \pm \text{Sem} = 39.1 \pm 1.54 = (37.6, 40.6)$$

Analysis of Variance

The analysis of variance (ANOVA)

- identifies sources of variability
- tests if variability due to treatments is real and not due to random variations

Concept of Analysis of Variance

The different *sources of variation* are dictated by the experimental design used:

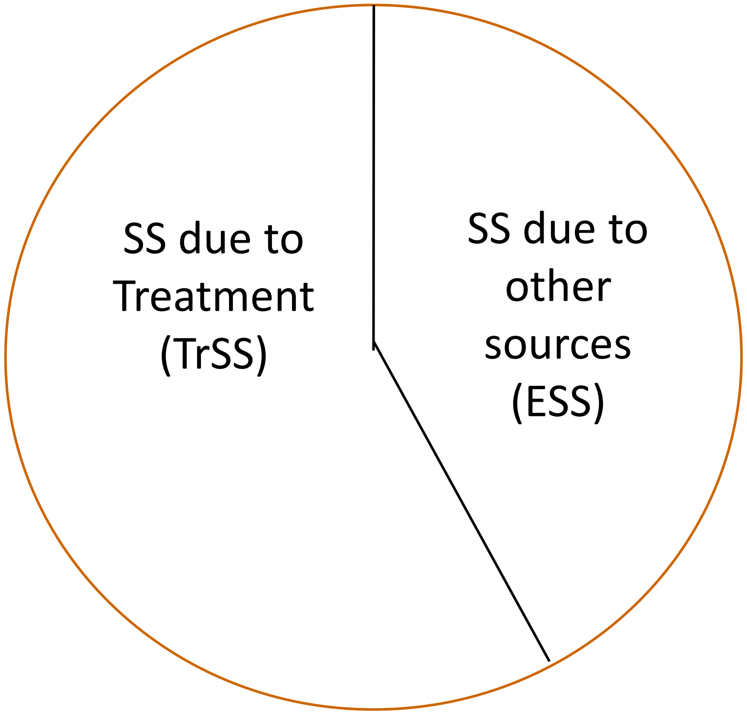
Completely randomized design (CRD)

TSS = treatment + exptal error

Randomized complete block design (RCBD)

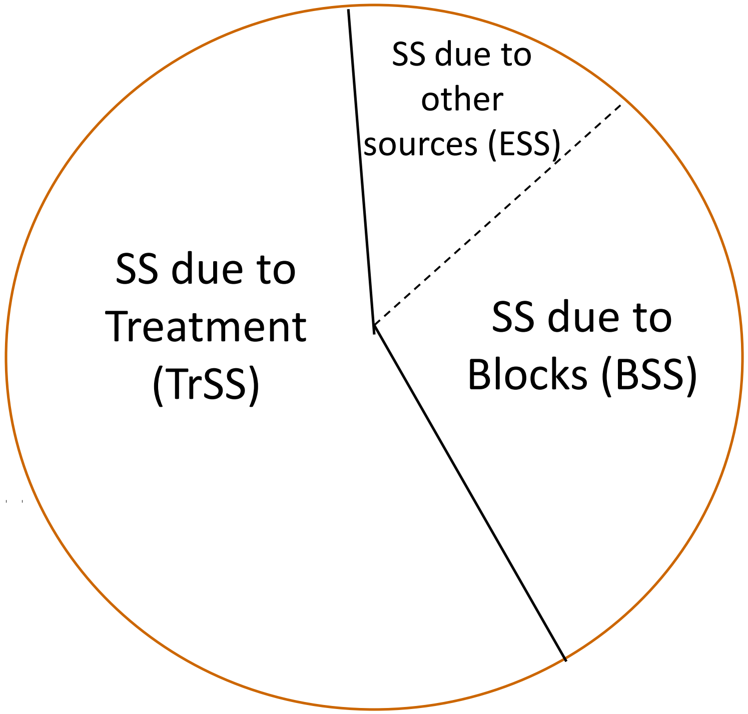
TSS = treatment + block + exptal error

CRD



$$\boxed{TSS = TrSS + ESS}$$

RCBD



$$\boxed{TSS = TrSS + BlockSS + ESS}$$

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ANOVA format

t = no. of treatments
r = no. of reps

Completely Randomized Design (CRD)				
SV	**df**	**SS**	**MS**	**F**
Treatment	t-1	TrSS	TrMS = TrSS / (t-1)	TrMS / EMS
Error	t(r-1)	ESS	EMS = ESS / t(r-1)	
Total	tr-1	TSS		

TrMS - estimate of variation among treatments
EMS - estimate of the inherent variations within treatments.

- The null hypothesis of “no treatment difference” can be done by comparing TrMS and EMS
- If there are no differences in treatment means, TrMS and EMS should be very similar.

One-way ANOVA (CRD)

The objective is to identify how much of this variation is explained by treatment and how much is unexplained.

Trt1	Trt2
40	40
40	40
40	40
40	40
40	40
40	40

Source of variation	df	SS	MS
Treatment	t-1 =1	0	0
Error	t(r-1)=2(6-1)=10	0	0
Total	tr-1 = 2(6)-1 = 11	0	0

One-way ANOVA (CRD)

The objective is to identify how much of this variation is explained by treatment and how much is unexplained.

Trt1	Trt2
36	40
36	40
36	40
36	40
36	40
36	40

Source of variation	df	SS	MS
Treatment	t-1 = 2-1 = 1	48	48
Error	t(r-1)=2(6-1)=10	0	0
Total	tr-1 = 2(6)-1 = 11	48	4.36

One-way ANOVA (CRD)

The objective is to identify how much of this variation is explained by treatment and how much is unexplained.

Trt1	Trt2
35	47
38	40
36	49
30	38
39	42
34	41

Source of variation	df	SS	MS
Treatment	t-1 =1	169.8	169.8
Error	t(r-1)=2(6-1)=10	142.2	14.2
Total	tr-1 = 2(6)-1 = 11	310.9	28.3

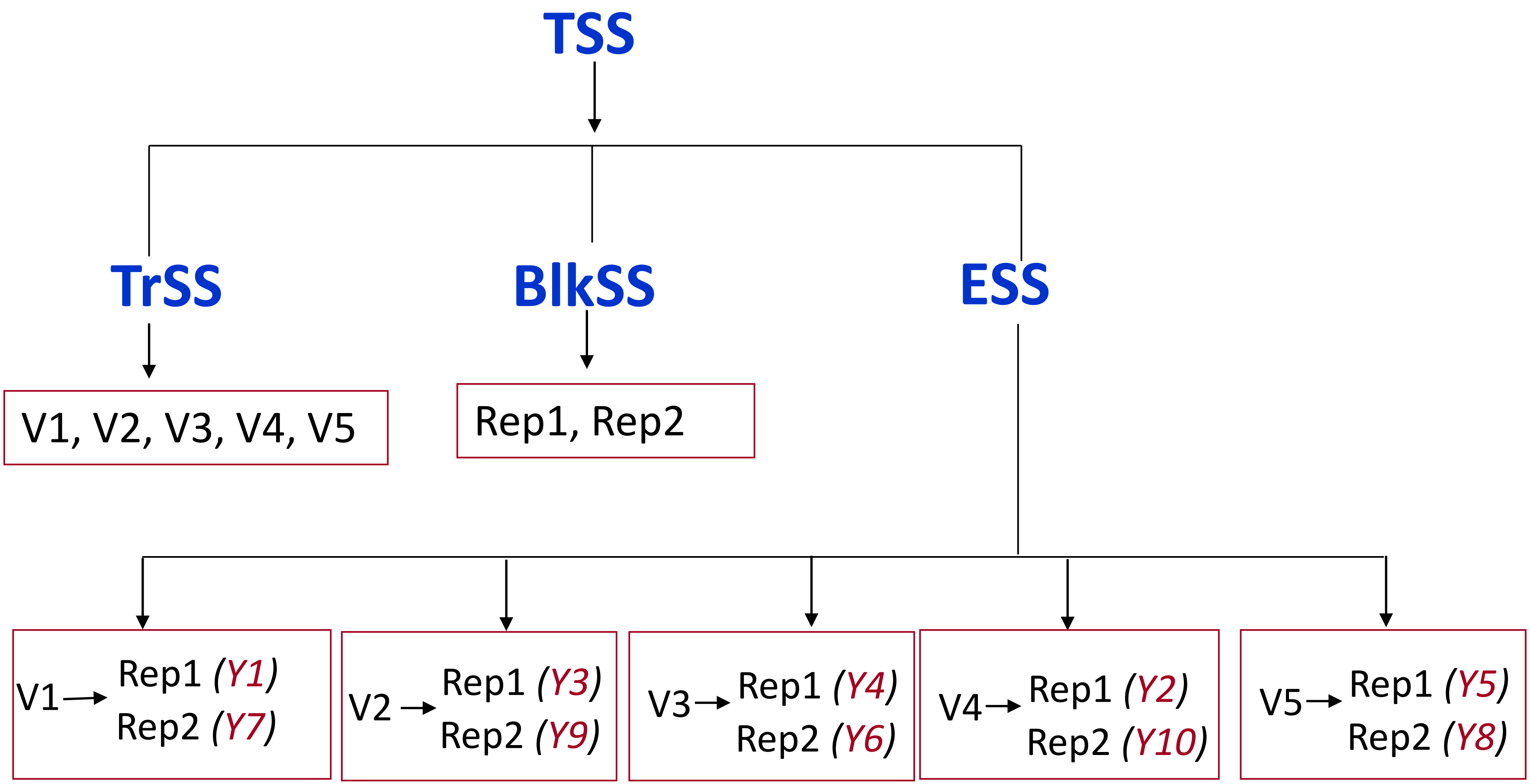
Is the variability between treatments different from random error ?

Concept of Analysis of Variance- RCBD

$$TSS = TrSS + BlockSS + ESS$$

Y1 V1	Y2 V4	Y3 V2	Y4 V3	Y5 V5	Block1 *(Rep 1)*
Y6 V3	Y7 V1	Y8 V5	Y9 V2	Y10 V4	Block2 *(Rep 2)*

TSS = TrSS + BlockSS + ESS

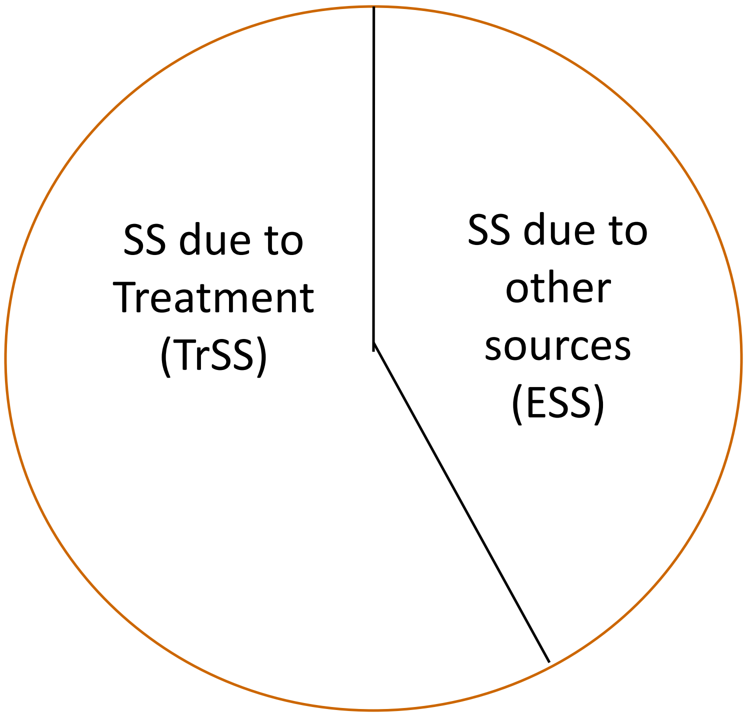


Analysis of Variance

- The ANOVA procedure partitions the total variation (TSS) into components

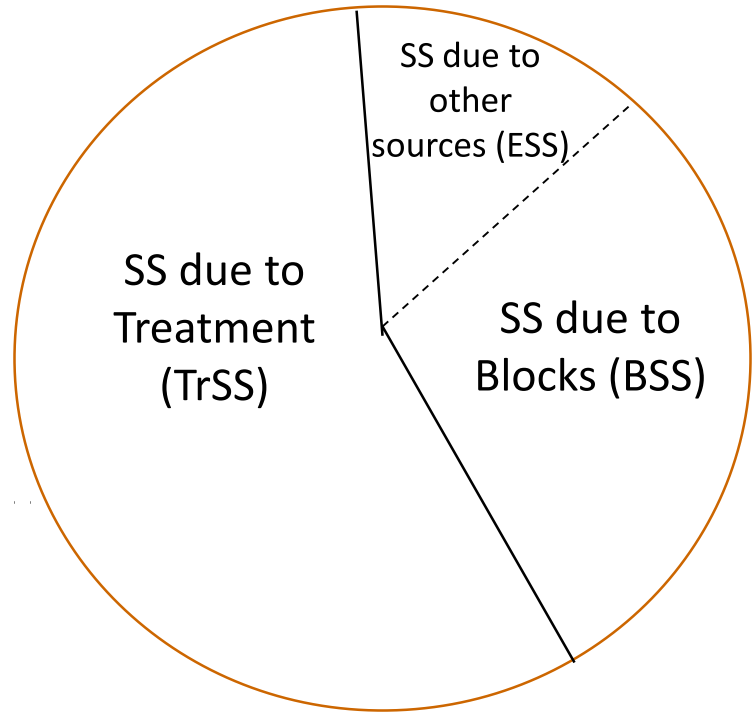
- Each component represents a different source of variation (SV) depending on the experimental design

CRD



$$TSS = TrSS + ESS$$

RCBD



$$TSS = TrSS + BlockSS + ESS$$

Hypothesis testing

Variety	Rep	Fruit wt
V1	1	39.4
V2	1	40.4
V3	1	26.2
V1	2	42.5
V2	2	41.6
V3	2	25.9
V1	3	37.0
V2	3	41.1
V3	3	26.8
V1	4	43.4
V2	4	41.5
V3	4	32.2

Ho: No differences among varieties (i.e., variability among varieties not different from random error)

Objective: To reject *Ho* so that it can be concluded that differences among varieties exist.

$P<0.01$	→	F is significant at 1%	→	**
$0.01 \leq P < 0.05$	→	F is significant at 5%	→	*
$P \geq 0.05$	→	F is not significant	→	ns

ANOVA Example - RCBD

ANOVA for fruit weight (kg/plot)

SV	df	SS	MS	F	Pr > F
Rep	3	30.4733	10.1578	2.67^{ns}	0.1410
Variety	2	457.4150	228.7075	60.21**	0.0001
Error	6	22.7917	3.7986		
Total	11	510.6800			
C.V. = 5.3 %					

** - significant at 1% level

^{ns} – not significant

Significant F-test

Significance level	What it means
1% (**)	chances are < 1 in 100 that all observed differences among the treatments are due to chance
5% (*)	chances are < 5 in 100 that all observed differences among the treatments are due to chance

Standard error of the mean

Estimate of the treatment mean: $\overline{\mathrm{X}}$

Standard error of the treatment mean (SEM):

$$= \sqrt{\frac{\mathrm{var}}{\mathrm{n}}} = \sqrt{\frac{\mathrm{EMS}}{\mathrm{r}}}$$

$$\mathbf{SEM} = \sqrt{\frac{3.7986}{4}} = \mathbf{0.97}$$

Measures of Variation

Variance = EMS or MSE

Standard deviation (STD) = $\sqrt{EMS}$

Standard error (SE) = $\sqrt{\dfrac{EMS}{r}}$

Standard error of the difference (SED) = $\sqrt{\dfrac{2\,(EMS)}{r}}$

No.of reps
(or samples)

Standard error of the difference

Estimate of the difference between 2 treatment means:

$$\overline{X}_i - \overline{X}_j$$

Standard error of the difference between 2 means (SED)

$$= \sqrt{\frac{2\text{EMS}}{\text{r}}}$$

$$\text{SED} = \sqrt{\frac{2(3.7986)}{4}} = 1.38$$

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Least Significant Difference (LSD)

$$LSD_{\alpha} = (t_{\alpha,\, n})\ SED$$

SED = is the standard error of the difference

t_{α} = is the tabular **t** value at α level of significance and **n** error degrees of freedom

t-table

df	t-value 5%	t-value 1%
1	12.70600	63.65699
2	4.30297	9.92509
3	3.18212	5.84016
4	2.77626	4.60521
5	2.57049	4.03249
6	2.44689	3.70711
7	2.36465	3.49886
8	2.30606	3.35469
9	2.26223	3.24918
10	2.22823	3.16871
11	2.20108	3.10536
12	2.17891	3.05420

$t_{(0.05,\ 6)} = 2.45$

$t_{(0.01,\ 6)} = 3.71$

Least Significant Difference (LSD)

$$LSD_{.05} = t \times SED$$

$$= 2.45 \times 1.38$$

$$= 3.38$$

$$LSD_{.01} = t \times SED$$

$$= 3.71 \times 1.38$$

$$= 5.12$$

If the difference between 2 treatment means is greater than the LSD value, then the means are significantly different.

LSD example

$LSD_{.05} = t \times SED$
$= 2.45 \times 1.38$
$= 3.38$

$LSD_{.01} = t \times SED$
$= 3.71 \times 1.38$
$= 5.12$

Mean difference between varieties:

V1 = 5.32
V2 = 9.01

Difference: 9.01 - 5.32 = 3.69

Since treatment mean difference (3.69) is greater than the $LSD_{.05}$=3.38, then the treatment means are significantly different at 5%, but not at 1% level.

Using LSD for multiple comparison

Trt	Mean
T1	33.5
T2	38.4
T3	33.0
T4	42.5
T5	39.6
T6	31.2

$LSD_{.05} = 7.3$

Trt	Mean
T4	42.5
T5	39.6
T2	38.4
T1	33.5
T3	33.0
T6	25.9

1. Arrange means in descending order.
2. Subtract the LSD from the highest mean: $42.5 - 7.3 = 35.2$

Using LSD for multiple comparison

Trt	Mean
T1	33.5
T2	38.4
T3	33.0
T4	42.5
T5	39.6
T6	31.2

$LSD_{.05} = 7.3$

Trt	Mean
T4	42.5
T5	39.6
T2	38.4
T1	33.5
T3	33.0
T6	31.2

3. All means less than the difference (35.2) are significantly different from the highest mean. T1,T3 and T6 are significantly different from T4.

4. Draw a vertical line connecting the means that are not significantly different from the largest mean.

Using LSD for multiple comparison

Trt	Mean
T1	33.5
T2	38.4
T3	33.0
T4	42.5
T5	39.6
T6	31.2

$LSD_{.05} = 7.3$

Trt	Mean
T4	42.5
T5	39.6
T2	38.4
T1	33.5
T3	33.0
T6	31.2

5. Repeat process using the 2nd highest mean. → 39.6 – 7.3 = 32.3

6. Only T6 is significantly different from T5. Draw another vertical line connecting the means that are not significantly different from T5.

7. Repeat process using the 3rd highest mean. → 38.4 – 7.3 = 31.1

Using LSD for multiple comparison

Trt	Mean
T1	33.5
T2	38.4
T3	33.0
T4	42.5
T5	39.6
T6	31.2

$LSD_{.05} = 7.3$

Trt	Mean
T4	42.5
T5	39.6
T2	38.4
T1	33.5
T3	33.0
T6	31.2

a b c

8. Since no means are lower than the difference, there are no treatments significantly different from T2. Draw another vertical line connecting T2 and the rest of the means. Assign a letter to each vertical line.

Using LSD for multiple comparison

Trt	Mean
T1	33.5
T2	38.4
T3	33.0
T4	42.5
T5	39.6
T6	31.2

$\longrightarrow$

$LSD_{.05} = 7.3$

Trt	Mean	
T4	42.5	a
T5	39.6	ab
T2	38.4	abc
T1	33.5	bc
T3	33.0	bc
T6	31.2	c

9. Use of letters, without the vertical line.

Example of mean comparison using LSD

Packaging	No of reps	Weight loss (%)	Mean difference
MAP (M)	3	41.2	
PE (P)	3	40.6	(M-P) 41.2 – 40.6 = 0.6 ^{ns}
Open (O)	3	27.8	(M-O) 41.2 – 27.8 = 13.4 **
			(P-O) 40.6 – 27.8 = 12.8 **
LSD (0.05) = 3.9			
LSD (0.01) = 5.6			

Non-significant F-test

What does a nonsignificant (ns) F-test mean?

ANOVA for tomato fruit firmness from a postharvest trial in CRD involving 6 treatments and 3 replications

SV	df	SS	MS	F	Pr > F
Treatment	5	2.9625	0.5925	2.48^{ns}	0.1034
Error	12	2.8692	0.2391		
Total	17	5.8317			

C.V. = 12.2 %

ns - not significant

Non-significant F-test

$$\boxed{P \geq 0.05}$$

the experiment fails to detect **significant** differences among treatments or among blocks

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Non-significant F-test

Does not mean that all treatments are the same

- experimental error is large
- very small treatment difference
- or both

Two-way ANOVA - RCBD

Ho: C32 = C99 = Ck

Ha: C32 ≠ C99 ≠ Ck

Block			
1	33 C32	12 Ck	52 C99
2	13 Ck	48 C99	30 C32
3	30 C32	15 Ck	58 C99
4	53 C99	34 C32	18 Ck

Chili Variety	Block	Fruit weight (g)
C32	1	33
Ck	1	12
C99	1	52
Ck	2	13
C99	2	48
C32	2	30
C32	3	30
Ck	3	15
C99	3	58
C99	4	53
C32	4	34
Ck	4	18

Two-way ANOVA - RCBD

Ho: C32 = C99 = Ck   Ha: C32 ≠ C99 ≠ Ck

ANOVA for fruit weight (g) of chili from a trial involving

3 varieties and 4 replications

SV	df	SS	MS	F	Pr > F
Replication	3	40.0000	13.3333	1.80^{ns}	0.2477
Variety	2	2935.5000	1467.7500	971.90 **	<0.0001
Error	6	44.5000	7.4167		
Total	11	3020.0000			

C.V. = 8.3 %

** significant at P<0.01; ^{ns} - not significant

ANOVA based on RCBD

(6 bacterial strains and 3 reps)

ANOVA for disease incidence

SV	df	SS	MS	F	Pr > F
Replication	2	0.3534	0.1767	39.54**	<0.0001
Strains	5	0.5356	0.1071	23.97 **	<0.0001
Error	10	0.0447	0.0045		
Total	17	0.9336			

C.V. = 15.7 %

** significant at P<0.01

Factorial experiments

- Two or more factors are tested simultaneously in a single trial
- Objective is to assess interaction between test factors

Factorial experiments (RCBD)

Objective: To determine the effect of fertilizer application on yield of chili peppers

Treatments: 3 Nrates = 0, 60, 90 kg/ha,
2 chili varieties (V1, V2), 4 reps

Trt No.	Trt combinations	
	Nitrogen (kg/ha)	Variety
1	0	V1
2	60	V1
3	90	V1
4	0	V2
5	60	V2
6	90	V2

Source of variation	df	
Block(rep)	r-1	4-1= **3**
Factor A	a-1	3-1= **2**
Factor B	b-1	2-1= **1**
A x B	(a-1)(b-1)	(3-1)(2-1)= **2**
Error	(r-1)(ab-1)	(4-1)(6-1)= **15**
Total	rab-1	(4)(3)(2)-1= **23**

Factorial experiments

Two or more factors are tested simultaneously in a single trial

Example: To determine the effect of packaging on firmness (kg) of two tomato varieties, a 2x3 factorial experiment in RCBD was conducted.

Block						
1	**w/P** Ck ***1.15***	**Wo/P** CLN ***1.28***	**Wo/P** TLCV ***1.40***	**w/P** CLN ***2.10***	**Wo/P** Ck ***1.70***	**w/P** TLCV ***1.63***
2	**Wo/P** TLCV ***1.80***	**w/P** Ck ***1.03***	**Wo/P** Ck ***1.65***	**Wo/P** CLN ***1.37***	**w/P** TLCV ***1.53***	**w/P** CLN ***2.15***
3	**w/P** CLN ***2.65***	**Wo/P** CLN ***1.48***	**w/P** TLCV ***1.58***	**Wo/P** Ck ***1.55***	**w/P** Ck ***1.09***	**Wo/P** TLCV ***1.85***

Factorial experiments

Packaging	Variety	Rep 1	Rep 2	Rep 3
with	TLCV	1.63	1.53	1.58
with	CLN	2.10	2.15	2.65
with	Ck	1.15	1.03	1.09
w/out	TLCV	1.40	1.80	1.85
w/out	CLN	1.28	1.37	1.48
w/out	Ck	1.70	1.65	1.55

Interaction →

SV	df	SS	MS	F	Pr > F
Replication	2	0.0151	0.0076	0.50^{ns}	0.6223
Packaging (P)	1	0.4020	0.4020	26.49 **	0.0004
Variety (V)	2	0.4588	0.2294	15.12 **	0.0009
V x P	2	0.1506	0.0753	4.96 *	0.0319
Error	10	0.1518	0.0152		
Total	17	1.1783			
C.V. (%) = 29.7					
**, * significant at P<0.01 and P<0.05, respectively;					
^{ns} not significant					

Interaction

- Interaction is the change in the effect of one factor when another factor varies.

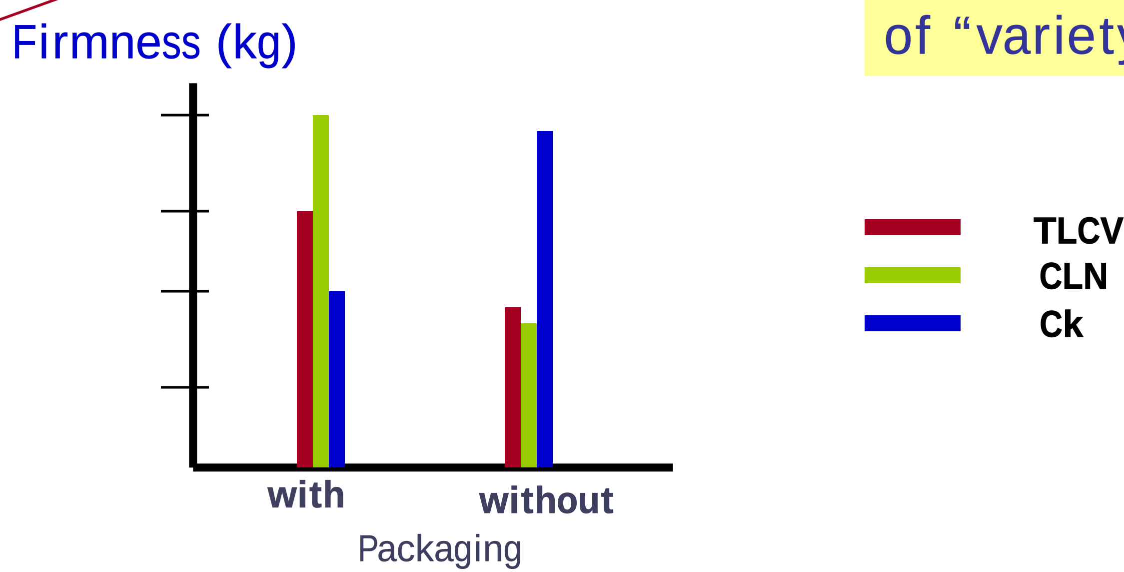
- Can be measured only if two factors are tested together in the same experiment.

Interaction

Variety	Packaging: with	Packaging: w/out	Variety_mean
TLCV	1.7 b	1.7 b	1.7
CLN	3.8 a	1.1 b	2.5
Ck	0.9 c	2.6 a	1.8
Packaging_mean	2.1	1.8	

main effect of "variety"

main effect of "packaging"



Multi-location trial: 6 varieties, 4 reps, 2 locations

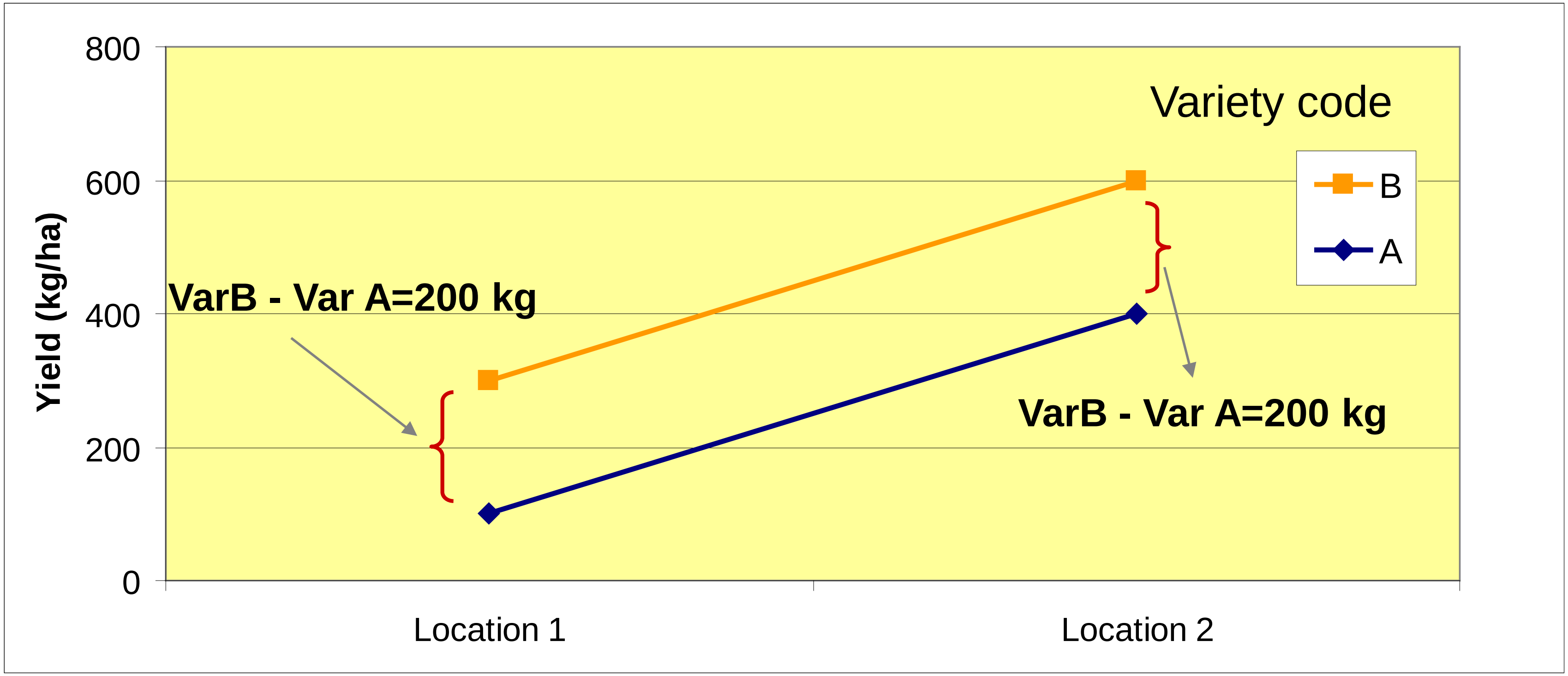
Individual analysis

	Degrees of freedom (DF)	
SV	Location1	Location2
Rep	3	3
Variety	5	5
Error	15	15
Total	23	23

Combined analysis over 2 locations

SV	DF
Location (L)	1
Reps w/in location	6
Variety (V)	5
V x L	5
Pooled error	30
Total	47

Types of GxE Interaction



No interaction: varieties have the same performance for a given trait in both locations; ranking of variety is unchanged between locations.

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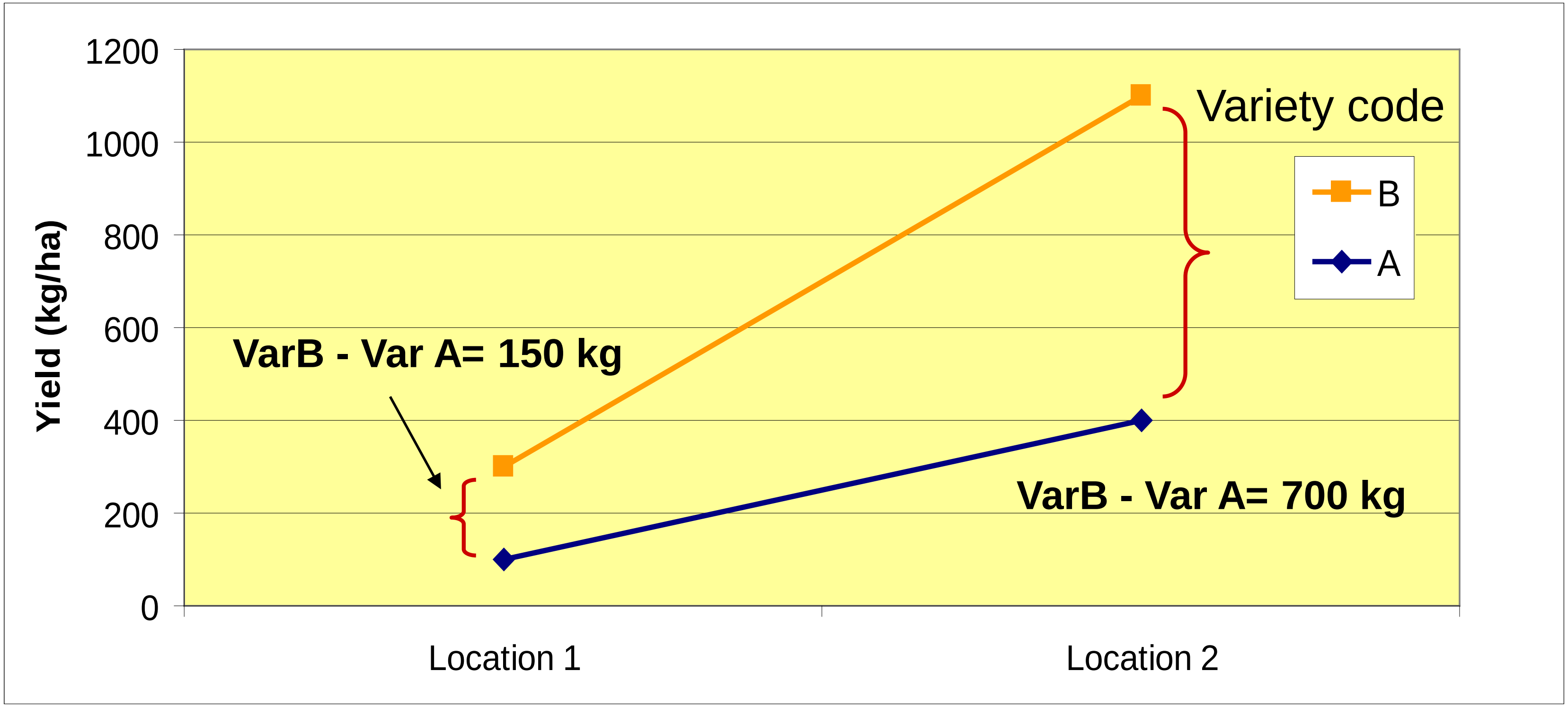
Types of GxE Interaction



With interaction - **(Case 1):** Yield varies greatly between locations; ranking of variety is unchanged

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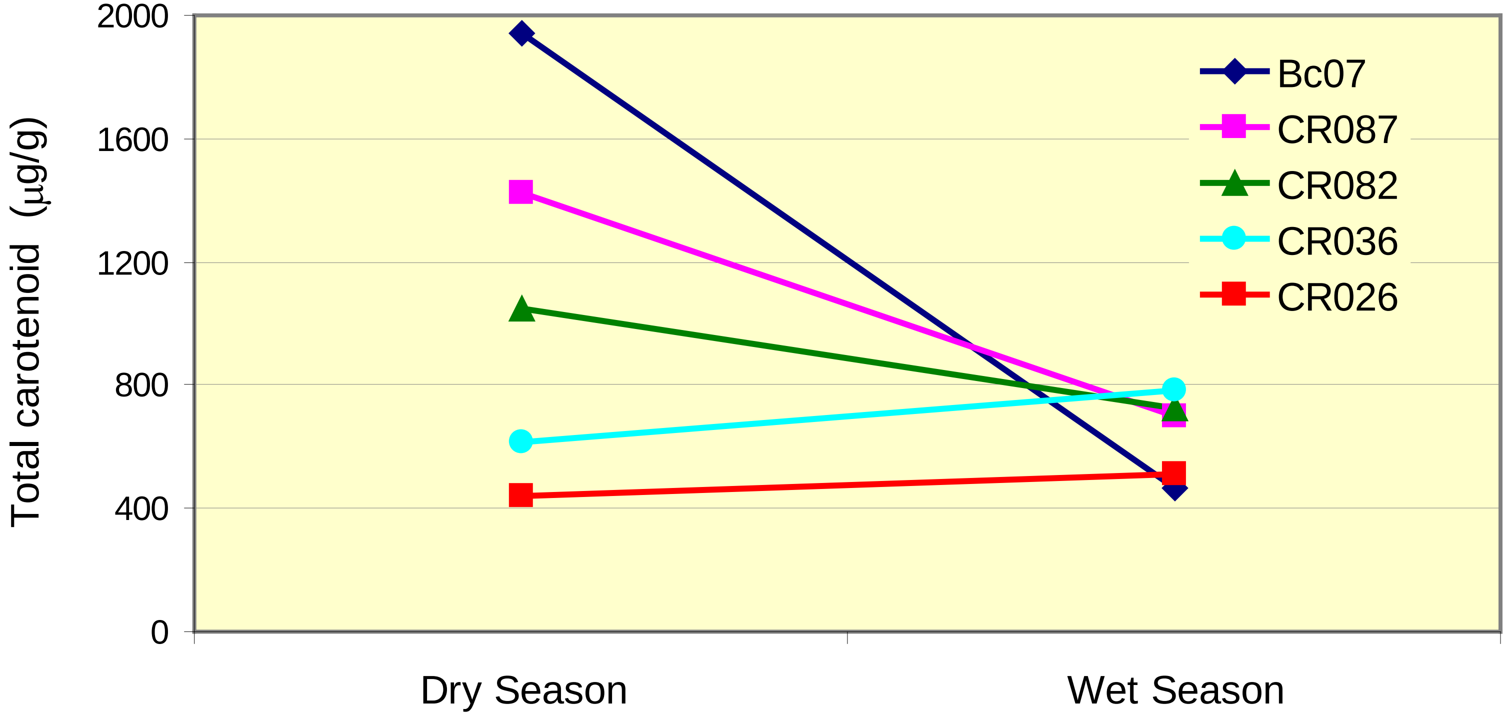
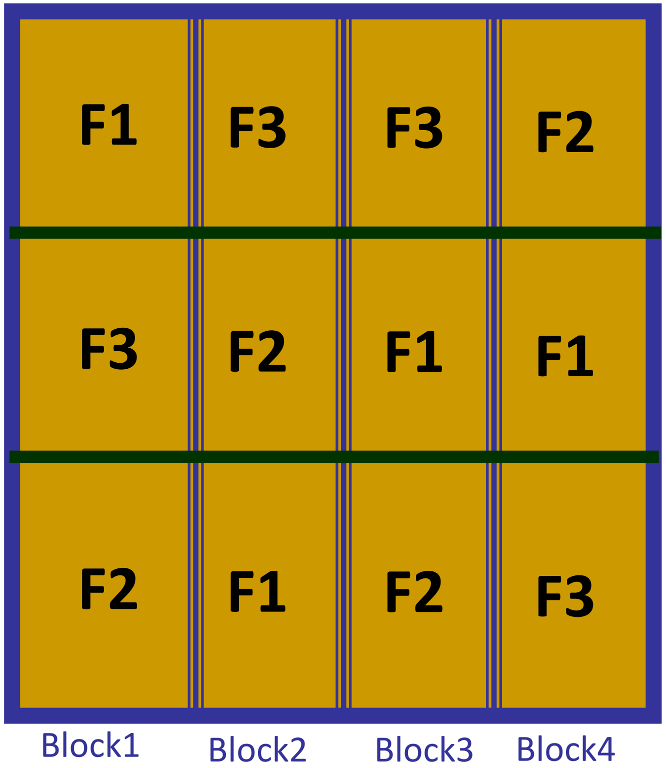
Types of GxE Interaction



With interaction - (Case 2): Carotenoid content varies greatly between seasons; ranking of varieties changes with season.

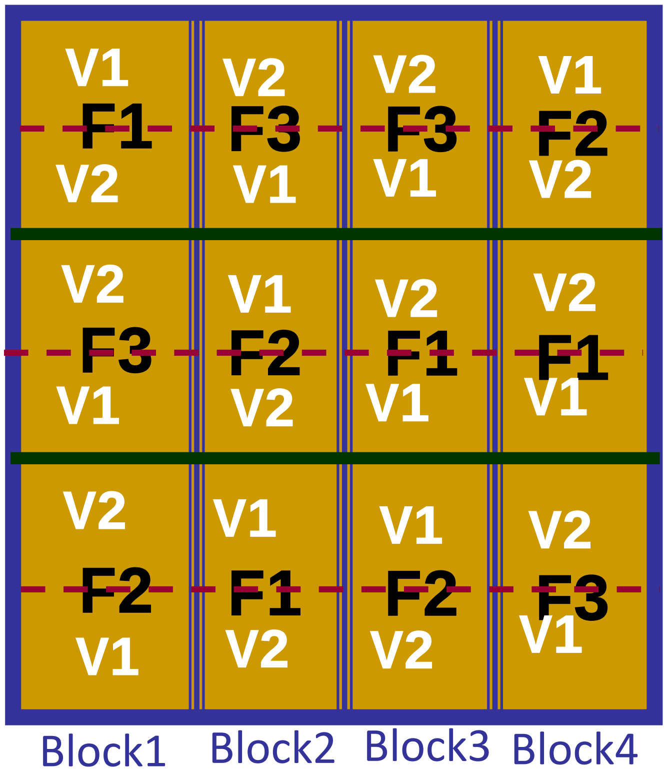
Split Plot Design



Source of variation	df	
Mainplot:		
Block	r-1	4-1= **3**
Fertilizer (F)	f-1	3-1= **2**
Error (a)	(r-1)(f-1)	(3)(2) = **6**
Subplot:		

3 fertilizer trts (MP), 2 varieties (SP), in 4 reps

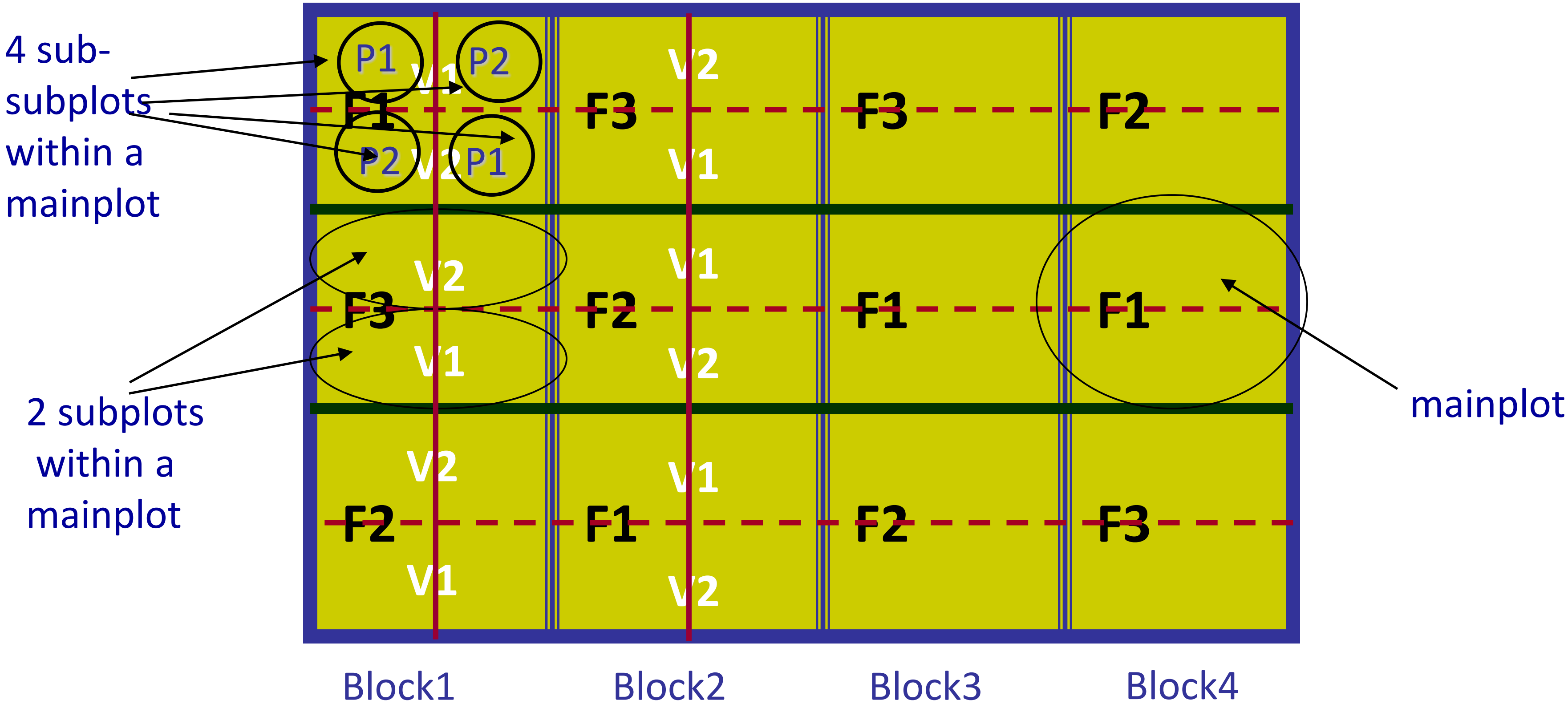
Split Plot Design



Source of variation	df	
Mainplot:		
Block	r-1	4-1= **3**
Fertilizer (F)	a-1	3-1= **2**
Error (a)	(r-1)(a-1)	(3)(2) = **6**
Subplot:		
Variety (V)	b-1	2-1 = **1**
F x V	(a-1)(b-1)	(1)(2) = **2**
Error (b)	a(r-1)(b-1)	3(3)(1) = **9**
Total	rab-1	4(3)(2)-1 = **23**

3 fertilizer trts (MP), 2 varieties (SP), in 4 reps

Split-split Plot Design : Layout



3 fertilizer trts (MP), 2 varieties (SP),
2 plant spacing (SSP) in 4 reps

Split-split Plot Design: ANOVA

Source of variation	df	
Mainplot:		
Block	r-1	4-1= **3**
Fertilizer (F)	a-1	3-1= **2**
Error (a)	(r-1)(a-1)	(3)(2) = **6**
Subplot:		
Variety (V)	b-1	2-1 = **1**
F x V	(a-1)(b-1)	(1)(2) = **2**
Error (b)	a(r-1)(b-1)	3(3)(1) = **9**
Sub-subplot:		
Plant spacing (P)	c-1	2-1 = **1**
F x P	(a-1)(c-1)	(3-1)(2-1) = **2**
V x P	(b-1)(c-1)	(2-1)(2-1) = **1**
F x V x P	(a-1)(b-1)(c-1)	(3-1)(2-1)(2-1) = **2**
Error (c)	ra(b-1)(c-1)	4(3)(2-1)(2-1) = **12**
Total	rabc-1	4(3)(2)(2)-1 = **47**

Coefficient of variation (CV)

$$CV = \left(\frac{\sqrt{EMS}}{\overline{X}} \right) \times 100$$

- indicates the degree of precision with which the treatments are compared
- the higher the CV, the lower the reliability of the experiment

Coefficient of variation (CV)

<u>CVs vary with</u>

- type of expt
- crop
- character measured

Test procedures for pair comparisons

- Least Significant Difference (LSD)
  - used for **planned** pair comparisons
- Multiple Range Tests (Tukey's, Scheffe's)
  - applicable to **unplanned** pair comparisons
- Single DF contrasts (PSS)

Multiple Range Test

- Each treatment mean can be compared with every other treatment mean

- provides different critical values for each pair of treatments being compared.

One- way table of means for factorial treatments

Packaging	Variety	No. of reps	Firmness	Multiple range comparison
with	TLCV	3	1.68	a
with	CLN	3	1.63	a
with	Ck	3	1.58	ab
without	TLCV	3	1.38	b
without	CLN	3	1.13	c
without	Ck	3	1.09	c

Two-way table of means for factorial treatments

Variety	Packaging		V_mean	Mean difference
	without	with		(with-without)
TLCV	1.58 ab	1.68 a	1.63	0.10^{ns}
CLN	1.13 c	1.38 b	1.26	0.25 *
Ck	1.09 c	1.63 a	1.36	0.54 **
P_mean	1.27	1.56	1.42	0.29

Misuses of multiple comparison procedures

- When treatments have an obvious structure
- When treatments are quantitative such as rates of fertilizer, plant density, seeding rate, or time
- Factorial treatment combinations are compared by multiple range tests without consideration of significant interactions.

Mean Separation Tests

- **Constant LSD.** In this category, a single LSD value is computed and used to compare all pairs of means.

  Ex. Fisher's LSD, Tukey's HSD

- **Variable critical values.** In this category, the means are ranked and the magnitude of the LSD is determined by the number of intervening means between the two means being compared.

  Ex. Duncan's multiple range test (DMRT), Waller Duncan