How deep is your playbook?

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Preliminaries

For Math Awareness Month in April
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Joint work with Eric B. Kahn, Bloomsburg University
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To appear in AMS publication and on the MAM website
Have you ever been watching a game and been frustrated with the play call?
Introduction

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Do you think you can do better?
Better than him?
Better than him?
Outline

1 Mathematics
   1 Algebra
   2 Combinatorics

2 Football
   1 The Game
   2 The Math

3 Defensive Formations
   1 3-4
   2 4-3
   3 Nickel
   4 Dime

4 Conclusion
Definition

An equivalence relation $\mathcal{R}$ on a set $S$ is a subset of all possible pairs in $S \times S$ that is reflexive, symmetric, transitive.
An equivalence relation on the set of real numbers $\mathbb{R}$ is $xRy$ if $|x| = |y|$.
Example

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Algebra Example

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Example

An equivalence relation on the set of real numbers \( \mathbb{R} \) is \( x \mathcal{R} y \) if \( |x| = |y| \).

1. Reflexive: Is \( x \mathcal{R} x \)? Yes, \( |x| = |x| \).
2. Symmetric: If \( x \mathcal{R} y \), is \( y \mathcal{R} x \)?
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2. Symmetric: If $x \mathcal{R} y$, is $y \mathcal{R} x$? Yes, if $|x| = |y|$, then $|y| = |x|$.
Example

An equivalence relation on the set of real numbers \( \mathbb{R} \) is \( x \sim y \) if \( |x| = |y| \).

1. Reflexive: Is \( x \sim x \)? Yes, \( |x| = |x| \).
2. Symmetric: If \( x \sim y \), is \( y \sim x \)? Yes, if \( |x| = |y| \), then \( |y| = |x| \).
3. Transitive: If \( x \sim y \) and \( y \sim z \), is \( x \sim z \)?
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3. Transitive: If $x \mathcal{R} y$ and $y \mathcal{R} z$, is $x \mathcal{R} z$? Yes, if $|x| = |y|$ and $|y| = |z|$, then $|x| = |z|$.
Example

The relation on the set of real numbers $\mathbb{R}$ where $x \mathcal{R} y$ if $x < y$ is NOT an equivalence relation.
### Example

The relation on the set of real numbers $\mathbb{R}$ where $x R y$ if $x < y$ is **NOT** an equivalence relation.

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The relation on the set of real numbers $\mathbb{R}$ where $x R y$ if $x \leq y$ is **NOT** an equivalence relation.

The symmetric property fails, $2 \leq 3$, but $3 \not\leq 2$. 

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### Example

The relation on the set of real numbers $\mathbb{R}$ where $x R y$ if $x + y \leq 5$ is **NOT** an equivalence relation.

The transitive property fails, $3 + 1 \leq 5$ and $1 + 4 \leq 5$, but $3 + 4 \not\leq 5$. 
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Algebra Non-examples

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The transitive property fails, $3 + 1 \leq 5$ and $1 + 4 \leq 5$, but $3 + 4 \not\leq 5$. 
A combination counts unordered subsets of a given set.
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$$\binom{n}{k} = \frac{n!}{k!(n-k)!}$$
We count the number of ways to choose one group of 3 people from a class with 10 students. We have
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We count the number of ways to choose one group of 3 people from a class with 10 students. We have

\[
\binom{10}{3} = \frac{10!}{3!(10-3)!} = \frac{10 \cdot 9 \cdot 8 \cdot 7!}{3 \cdot 2 \cdot 1 \cdot 7!} = \frac{10 \cdot 9 \cdot 8}{3 \cdot 2 \cdot 1} = 120
\]
The playing surface of a NFL field is 100 yards long and 53.3 yards wide.
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The goal of the defense is to prevent the opposing team from traversing the field and reaching an end zone.
There are exactly 11 players of each team on the field during any play.
Players and Field

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- There are 4 different types of players in a defensive formation.

- Linemen
- Linebackers
- Cornerbacks
- Safeties
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- We divide the length of the field vertically into 4 tiers.
  1. Defensive line
  2. Mid
  3. Nickel
  4. Deep
Tiers

- Deep
- Nickel
- Mid
- Defensive Line
The 3-4 has exactly 3 linemen and 4 linebackers.
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- DL DL DL CBCB
- LB LB LB LB
- S S
- LB LB LB LB
- CB DL DL DL CB
The 4-3 has exactly 4 linemen and 3 linebackers.
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\[ S \quad S \quad LB \quad LB \quad LB \quad CB \quad DL \quad DL \quad DL \quad DL \quad CB \]
The Nickel has exactly 4 linemen, 2 linebackers, and 3 corners.
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The Dime is made up of exactly 4 corners, 2 safeties, and at least one linebacker.
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\[
\begin{array}{c c}
\text{S} & \text{S} \\
\text{CB} & \text{CB} \\
\text{LB} & \text{LB} \\
\text{CB} & \text{DL} & \text{DL} & \text{DL} & \text{CB}
\end{array}
\]
Mirror Symmetry

**Definition**

Two defensive alignments will be considered *mirror equivalent*, or simply *equivalent*, if at each level the order of the players from right to left is reversed.
The following two formations are mirror equivalent.

\[ \begin{array}{ccc}
\cdot B & \cdot B \\
\cdot B & \cdot B & \cdot S \\
\cdot M & \cdot B & \cdot M & \cdot M & \cdot B
\end{array} \quad \begin{array}{ccc}
\cdot B & \cdot B \\
\cdot B & \cdot B & \cdot S \\
\cdot M & \cdot B & \cdot M & \cdot M & \cdot B
\end{array} \]
This formation is mirror equivalent to itself.
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We call such a formation *self-symmetric*.
Restrictions

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2. There must be at least two linemen on the field.
3. At most two linebackers can line up at the defensive line level.
4. All other linebackers must line up at the mid level.
5. Cornerbacks can line up at any level.
6. Safeties can line up at the deep or mid level.
7. There must be exactly 2 safeties on the field with at least one at the deep level.
8. Only corners will line up in the exterior regions of the field outside the linebackers and safeties.
9. Two linebackers cannot stand side by side on the defensive line level.
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Counting Approach

- Determine which players are fixed.
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- Insert the remaining players into the formation beginning with linebackers, then the safety, and ending with the corners.
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- Determine which players are fixed.
- Insert the remaining players into the formation beginning with linebackers, then the safety, and ending with the corners.
- When inserting the linebackers and the safety, we consider whether a formation is self-symmetric.
- When inserting the corners, we consider the number of way they can line up with or without respect to the mirror equivalence.
Counting the 3-4 defense

Players

3 Linemen
4 Linebackers
2 Safeties
2 Corners
Counting the 3-4 defense

Players

- 3 Linemen
- 4 Linebackers
- 2 Safeties
- 2 Corners
Fixed players

Because of the restrictions, the three linemen, two linebackers, and one safety are fixed at specific levels.
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Place the Linebackers

There are three scenarios for placing the other 2 linebackers.

1. Both on the line and this can be done in three ways:
   1. both outside all linemen (ss), one way
   2. one between two linemen and one outside all linemen in two ways, that is, either one or two linemen between the two linebackers on the line
   3. both between two linemen (ss), one way.
2. Both on mid level (ss) one way.
3. One on the defensive line and one at the mid level. There are 2 spots for the one on the line:
   1. inside in one way
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To count these up we have 3 (ss) formations and 4 non-(ss) formations.
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Place the Safety

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1. **Deep**
   - We have 3 self-symmetric formations and 4 formations which are not self-symmetric.
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1. **Deep**
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2. **Mid**
   - Parts (1) and (3) are self-symmetric, so the safety can be placed in each in 2 ways, between the two line backers (ss) and outside the line backers. Neither formation in part (2) is self-symmetric, so the safety can stand in \((\binom{3}{1}) = 3\) different ways, on the outside on either side or in between the two line backers.

   - This formation is self-symmetric. We have 3 ways to place the last safety; in the center of the mid level with two line backers on either side (ss), between two linebackers with one on one side and three on the other, and outside the linebackers.

   - Neither formation is self-symmetric. The safety can be placed in \((\binom{4}{1}) = 4\) ways, between the linebackers two ways and outside the linebackers two ways, for each formation.
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Example with the Safety
Counting, we have:

Mid:
1 \cdot 2 + 1 \cdot 1 = 3 \text{ self-symmetric formations}

Mid & Deep:
3 + 3 = 6 \text{ self-symmetric formations}

Count so far:
18 + 4 = 22 \text{ alignments which are not self-symmetric}
Counting, we have:

- Mid

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We have two cases.

1. Both corners stand on the same side and same level.
2. Each corner stands on a different side or level.
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This can be done in \((8!)_1 = 8\) ways. Each of the 8 formations where the corners are standing on the same line and same side are symmetric to exactly one other. We have 4 different formations respecting mirror equivalence.
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There are 28 possible places to line up the corners. 4 formations of the 28 are self-symmetric. 12 placements have been counted twice. 4 + 12 = 16 total alignments with respect to mirror equivalence.
\( \binom{8}{2} = 28 \) possible places to line up the corners.
4 formations of the 28 are self-symmetric.
12 placements which have been counted twice.
4 + 12 = 16 total alignments with respect to mirror equivalence.
Totals

We have

\[8 + 28 = 36\] possible formations without regard to symmetry which are not self-symmetric.

\[4 + 16 = 20\] possible formations with regard to the mirror equivalence which we apply to the self-symmetric formations.

The number of non-equivalent 3-4 defensive formations is:

\[20 \cdot 6 + 36 \cdot 22 = 912\]
We have

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Similarly we count the non-equivalent alignments of the other 3 defensive formations.
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- 4-3: 1,000
- Nickel: 2,340
- Dime: 11,120

Thus there are exactly 15,372 possible defensive alignments!
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Do you still think you could do better?
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Thank you!