Recitation 10

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• Induction: Example using triominoes for \(2^n \times 2^n\) checkerboard missing one corner, see page 326.

• Problem 5.1.5: Using induction, prove:

\[
\forall n \geq 0 \quad 1^2 + 3^2 + \ldots + (2n + 1)^2 = \frac{(n + 1)(2n + 1)(2n + 3)}{3}
\]

We prove the property using mathematical induction:

1. Let’s state the property to prove:

\[
P(n) : 1^2 + 3^2 + \ldots + (2n + 1)^2 = \frac{(n + 1)(2n + 1)(2n + 3)}{3}
\]

2. We take \(n_0 = 0\) and prove \(P(0)\):

\[
P(0) = 1 = \frac{(1)(1)(3)}{3}
\]

We show that \(P(0)\) holds: \(1 = 1\). Therefore, \(P(0)\) is true.

3. What is the inductive hypothesis?

\[
P(k) : 1^2 + 3^2 + \ldots + (2k + 1)^2 = \frac{(k + 1)(2k + 1)(2k + 3)}{3}
\]

4. Assuming the base case and the inductive hypothesis, we want to prove:

\[
P(k + 1) : 1^2 + 3^2 + \ldots + (2k + 3)^2 = \frac{(k + 2)(2k + 3)(2k + 5)}{3}
\]

5. We start from \(1^2 + 3^2 + \ldots + (2k + 1)^2 + (2k + 3)^2\).

\[
\begin{align*}
1^2 + 3^2 + \ldots + (2k + 1)^2 + (2k + 3)^2 \\
= \frac{(k+1)(2k+1)(2k+3)}{3} + (2k + 3)^2 \\
= (2k + 3) \cdot \left( \frac{(k+1)(2k+1)+6k+9}{3} \right) \\
= (2k + 3) \cdot \left( \frac{2k^2+9k+10}{3} \right) \\
= \frac{(k+2)(2k+3)(2k+5)}{3}
\end{align*}
\]

Thus, \(P(k + 1)\) holds.
Consequently, by the PMI, $\forall n \geq 0 \ 1^2 + 3^2 + \ldots + (2n + 1)^2 = \frac{(n+1)(2n+1)(2n+3)}{3}$

• Now, prove the following: $3 \mid 2^{2n} - 1$ for $n \geq 1$.

1. First, we state the property to prove: $P(n) : 3 \mid 2^{2n} - 1$.

2. Base case is $n_0 = 1$. So $P(1) = 3 \mid 2^{2(1)} - 1$. Clearly, $2^{2(1)} - 1 = 4 - 1 = 3$, $3 \mid 3$, which is obvious. So, $P(1)$ holds.

3. Next, we state the inductive hypothesis: $P(k) : 3 \mid 2^{2k} - 1$ and assume that $P(k)$ holds.

4. Now, we have to prove that $P(k+1) : 3 \mid 2^{2k+2} - 1$ holds. We start from $2^{2k+2} - 1$. $2^{2k+2} - 1 = 4 \cdot 2^k - 1 = 4 \cdot (2^k - 1 + 1) - 1$.

   The inductive hypothesis gives that $3 \mid 2^{2k} - 1$ This, there is an integer $t$ such that $2^{2k} - 1 = 3t$. Thus,

   $2^{2k+2} - 1 = 4 \cdot (3t + 1) - 1 = 12t + 4 - 1 = 12t + 3 = 3 \cdot (4t + 1)$.

   Thus, $2^{2k+2} - 1$ is a multiple of 3. Hence, $P(k+1)$ holds.

Consequently, by the PMI, $\forall n \geq 1, \ 3 \mid 2^{2n} - 1$.

• A proof by strong induction.

Show that $\forall n \in \mathbb{N}, \ 12 \mid (n^4 - n^2)$.

1. First, we state the property:

   $P(n) : 12 \mid (n^4 - n^2)$

2. Base Case:

   (a) For $n = 1$: $1^4 - 1^2 = 0 = 12 \cdot 0$, so $P(1)$ is true.

   (b) For $n = 2$: $2^4 - 2^2 = 16 - 4 = 12 = 12 \cdot 1$, so $P(2)$ is true.

   (c) For $n = 3$: $3^4 - 3^2 = 81 - 9 = 72 = 12 \cdot 6$, so $P(3)$ is true.

   (d) For $n = 4$: $4^4 - 4^2 = 256 - 16 = 240 = 12 \cdot 20$, so $P(4)$ is true.

   (e) For $n = 5$: $5^4 - 5^2 = 625 - 25 = 600 = 12 \cdot 50$, so $P(5)$ is true.

   (f) For $n = 6$: $6^4 - 6^2 = 1296 - 36 = 1260 = 12 \cdot 105$, so $P(6)$ is true.

3. Strong Inductive Hypothesis Let $k \geq 6 \in \mathbb{N}$ and assume that $12 \mid (m^4 - m^2)$ for $1 \leq m < k$ where $m \in \mathbb{N}$.

4. We need to establish $P(k)$.

   Let $i = k - 5$. Because $i < k$, we can assume that $P(i)$ holds.

   Clearly $i + 6 = k + 1$.

   $(i + 6)^4 - (i + 6)^2$

   $= (i^4 + 24i^3 + 180i^2 + 864i + 1296) - (i^2 + 12i + 36)$

   $= (i^4 - i^2) + 24i^3 + 180i^2 + 852i + 1260$

   Because $P(i)$ holds, we have $i^4 - i^2 = 12 \cdot t$. 

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Further, $24i^3 + 180i^2 + 852i + 1260 = 12(2i^3 + 15i^2 + 71i + 105)$.  
Thus, $(i + 6)^4 - (i + 6)^2 = 12 \cdot t + 12(2i^3 + 15i^2 + 71i + 105) = 12(t + 2i^3 + 15i^2 + 71i + 105)$.  
Hence, $(i + 6)^4 - (i + 6)^2$ is a multiple of 12 and $12 \mid (k + 1)^4 - (k + 1)^2$.

We can finally state that by the principle of strong induction, $\forall n \in \mathbb{N}, \ 12 \mid (n^4 - n^2)$. 
