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Properties of Magic Squares of Squares

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A problem due to Martin LaBar is to find a 3x3 magic square with 9 distinct perfect square entries or prove that such a magic square cannot exist (LaBar [1]). This problem has been tied to various domains including arithmetic progressions, rational right triangles, and elliptic curves (Robertson [2]). However, there are some interesting properties that can be derived without ever leaving the domain of magic squares. I will assume that a solution exists and prove properties of such a solution. Any solution must have the form

$$\begin{array}{ccc} a^2 & b^2 & c^2 \\ d^2 & e^2 & f^2 \\ g^2 & h^2 & s^2 \end{array}$$

If M denotes the magic number, then M is the sum of each row, column, or main diagonal. We know from Gardner [3] that M must equal three times the middle square, so $M = 3e^2$.

Let t be the greatest common divisor of $a^2, b^2, c^2, d^2, e^2, f^2, g^2, h^2$ and s^2. If $t \neq 1$ then t is a square, thus we can divide all entries by t to produce a new solution with a smaller magic number(M/t). For this reason, it will be assumed throughout this paper that the entries are relatively prime$(t = 1)$.

Theorem 1.1 *All entries of the magic square must be odd.*

Proof: Using the fact that the the entries on the left side of the square must sum to M we get

$$a^2 + d^2 + g^2 = M = 3e^2$$

Hence $a^2 + g^2 = 3e^2 - d^2$, and in particular,

$$a^2 + g^2 \equiv 3e^2 - d^2 (\text{mod } 4)$$

With e odd and d even, we have $a^2 + g^2 \equiv 3 - 0 \equiv 3(\text{mod } 4)$. Taking e even and d odd gives $a^2 + g^2 \equiv 0 - 1 \equiv -1 \equiv 3(\text{mod } 4)$. This is impossible since

$a^2 + g^2 \equiv 0$ or $2(\text{mod } 4)$. Therefore, e and d must have the same parity. Both e and d odd gives $a^2 + g^2 \equiv 3 - 1 \equiv 2(\text{mod } 4)$. This implies that a and g must be odd. Both e and d even gives $a^2 + g^2 \equiv 0 - 0 \equiv 0(\text{mod } 4)$. This implies that a and g must be even. Thus $a \equiv g \equiv e \equiv d(\text{mod } 2)$.

Arguing in a similar fashion for the other sides of the square we find that $a \equiv b \equiv c \equiv d \equiv e \equiv f \equiv g \equiv h \equiv s \pmod 2$. Thus, if any element is even they are all even, contradicting the fact that the elements are relatively prime. Hence, all entries are odd. ■

Using the rows, columns and main diagonals that pass through the center of the square we have

$$a^2 + e^2 + s^2 = d^2 + e^2 + f^2 = b^2 + e^2 + h^2 = g^2 + e^2 + c^2 = 3e^2$$

from which it follows that

$$a^2 + s^2 = d^2 + f^2 = b^2 + h^2 = g^2 + c^2 = 2e^2$$

We can now prove the following theorem.

Theorem 1.2 *The only prime divisors of e are of the form $p \equiv 1(\text{mod } 4)$.*

Proof: We just need to show that no prime $p \equiv 3(\text{mod } 4)$ can divide e. We use the fact that the ring of Gaussian integers $Z[i]$ is a Unique Factorization Domain(UFD). Factoring the left side of $a^2 + s^2 = 2e^2$ in $Z[i]$, we get $(a + si)(a - si) = 2e^2$. Given an odd prime $p \in Z$, then p is prime in $Z[i]$ if and only if $p \equiv 3(\text{mod } 4)$(See Lemma 1.1 in the Appendix). Thus, assume we have a p such that $p \equiv 3(\text{mod } 4)$ and $p \mid e$. Then we must have either $p \mid (a + si)$ or $p \mid (a - si)$. If $p \mid (a + si)$, then $a + si = pk$ and by complex conjugation $a - si = \overline{pk} = p\overline{k}$. Hence $p \mid (a - si)$. But then p must also divide their sum and difference: $p \mid 2si$ and $p \mid 2a$. Hence $p \mid s$ and $p \mid a$ since p is odd and real.

Similarly, $p \mid d$, $p \mid f$, $p \mid b$, $p \mid h$, $p \mid g$, and $p \mid c$. Hence, p divides every entry which is impossible. ■

Theorem 1.3 *If a prime $p \equiv 3, 5(\text{mod } 8)$ divides a non-center entry then p also divides the center and the other entry in that line.*

Proof: Without loss of generality we prove the result for the a, e, s diagonal. We use the fact that the ring $Z[\sqrt{2}]$ is a UFD. Given an odd prime $p \in Z$, then p is prime in $Z[\sqrt{2}]$ if and only if $p \equiv 3, 5 \pmod 8$(See Lemma 1.2 in the Appendix).

Since $a^2 + s^2 = 2e^2$ implies $a^2 = -(s^2 - 2e^2)$, we can factor the right side of this equation in $Z[\sqrt{2}]$ to get

$$a^2 = -(s + e\sqrt{2})(s - e\sqrt{2}).$$

If $p \mid a$ and $p \equiv 3, 5 (\text{mod } 8)$, then either $p \mid (s + e\sqrt{2})$ or $p \mid (s - e\sqrt{2})$. If $p \mid (s + e\sqrt{2})$, then $s + e\sqrt{2} = pk$, and by conjugation $s - e\sqrt{2} = p\bar{k}$. Hence $p \mid (s - e\sqrt{2})$. Thus p divides their sum and difference: $p \mid 2s$ and $p \mid 2e\sqrt{2}$. Hence $p \mid s$ and $p \mid e$ since p is odd and rational. ■

Corollary 1.1 *No prime $p \equiv 3$(mod 8) divides any entry.*

Proof: If p divides some non-center entry, then by Theorem 1.3, p divides e. But from Theorem 1.2, we know that p cannot divide e since $p \equiv 3 (\text{mod } 8) \Rightarrow p \equiv 3 (\text{mod } 4)$. ■

Gardner [3] has shown that given any 3x3 magic square of distinct positive integers, there are three positive integers x, y, z so that the magic square can be written in the form

$$\begin{array}{ccc} x+y+2z & x & x+2y+z \\ x+2y & x+y+z & x+2z \\ x+z & x+2y+2z & x+y \end{array}$$

Looking at this we quickly see that $d^2 + h^2 = 2c^2$ with similar relations holding for the other corner entries. This relation can be stated as

Twice the corner entry equals the sum of the two middle-side entries that are not adjacent to the corner.

We can now prove the following theorem.

Theorem 1.4 *No prime $p \equiv 5$(mod 8) divides a middle-side entry.*

Proof: Without loss of generality, let the middle-side entry be d^2. Again, we use the fact that the ring $Z[\sqrt{2}]$ is a UFD. Given an odd prime $p \in Z$, then p is prime in $Z[\sqrt{2}]$ if and only if $p \equiv 3, 5 \pmod 8$ (See Lemma 1.2 in the Appendix).

Since $d^2 + h^2 = 2c^2$ implies $d^2 = -(h^2 - 2c^2)$, we can factor the right side of this equation in $Z[\sqrt{2}]$ to get

$$d^2 = -(h + c\sqrt{2})(h - c\sqrt{2})$$

If $p \mid d$ and $p \equiv 5 (\text{mod } 8)$ then either $p \mid (h + c\sqrt{2})$ or $p \mid (h - c\sqrt{2})$. If $p \mid (h + c\sqrt{2})$, then $h + c\sqrt{2} = pk$ and by conjugation $h - c\sqrt{2} = p\bar{k}$. Hence $p \mid (h - c\sqrt{2})$. Thus p divides their sum and difference: $p \mid 2h$ and $p \mid 2c\sqrt{2}$. Hence $p \mid h$ and $p \mid c$ since p is odd and rational. Since $p \mid h$ we can use the same argument to show that $p \mid f$ and $p \mid a$. But then, since $p \mid f$, we can use the same argument again to show that $p \mid b$ and $p \mid g$. Since p divides both a and s, p must also divide e. Hence p divides all entries, which is impossible. ■

Theorem 1.5 *If a prime $p \equiv 3$(mod 4) divides a corner entry then it divides the two middle-side entries that are not adjacent to the corner.*

Proof: Without loss of generality, let the corner entry be c^2. Again, we use the fact that the ring of Gaussian integers $Z[i]$ is a UFD. Factoring the left side of $d^2 + h^2 = 2c^2$ in $Z[i]$, we get $(d + hi)(d - hi) = 2c^2$. If $p \equiv 3(\text{mod } 4)$ then p is prime in $Z[i]$ (See Lemma 1.1 in the Appendix). Thus if $p \mid c$ and $p \equiv 3(\text{mod } 4)$, then either $p \mid (d + hi)$ or $p \mid (d - hi)$. If $p \mid (d + hi)$, then $d + hi = pk$, and by conjugation $d - hi = p\overline{k}$. Hence $p \mid (d - hi)$. Thus p divides their sum and difference: $p \mid 2d$ and $p \mid 2hi$. Hence $p \mid d$ and $p \mid h$ since p is odd and real. $\blacksquare$

All of these properties taken together severely restrict the possible placement of primes that are not of the form $p \equiv 1(\text{mod } 8)$. Given these restrictions, one might conjecture that if there is a solution, then all prime divisors of all entries are of the form $p \equiv 1(\text{mod } 8)$. This would greatly reduce the number of possibilities. It would also be interesting to disprove this conjecture by proving the opposite; namely, that any solution must have at least one entry with prime divisor $p \equiv 5, 7(\text{mod } 8)$.

APPENDIX

We need to know when an odd prime $p \in Z$ is also prime in the extensions $Z[i]$ and $Z[\sqrt{2}]$. The following two lemmas answer this question completely.

Lemma 1.1 *Given an odd prime $p \in Z$,*

$$p \equiv 3(\textit{mod } 4) \Leftrightarrow p \textit{ prime in } Z[i]$$

Proof: We use the fact that $Z[i]$ is a UFD.

First, we assume that $p \equiv 3(\text{mod } 4)$ and show that p must be prime in $Z[i]$. If p is composite in $Z[i]$ then p has a factorization $p = \alpha\beta$ with $N(\alpha) > 1$ and $N(\beta) > 1$. Taking the norm of both sides we get $p^2 = N(\alpha)N(\beta)$. It is not possible for p^2 to divide $N(\alpha)$ or $N(\beta)$ since this would imply $N(\beta) = 1$, $N(\alpha) = 1$ respectively. Hence $N(\alpha) = p$ and $N(\beta) = p$. From the former we get $p = N(\alpha) = x^2 + y^2$ for some $x, y \in Z$. Thus $p \equiv 0, 1, 2(\text{mod } 4)$ which is a contradiction. $\blacksquare$

Now we assume that p is prime in $Z[i]$ and show that $p \equiv 3(\text{mod } 4)$. If $p \equiv 1(\text{mod } 4)$ then the equation $x^2 \equiv -1(\text{mod p})$ has a solution. Hence $x^2 + 1 = kp$. Factoring in $Z[i]$ we get $(x + i)(x - i) = kp$. Since p is prime, it must divide one of the factors and by complex conjugation it divides both. Therefore p divides their difference: $p \mid 2i$. This is impossible since p is odd and real (Beukers [4]). $\blacksquare$

Lemma 1.2 *Given an odd prime $p \in Z$,*

$$p \equiv 3, 5(\textit{mod } 8) \Leftrightarrow p \textit{ prime in } Z[\sqrt{2}]$$

Proof: We use the fact that $Z[\sqrt{2}]$ is a UFD.

First, we assume that $p \equiv 3, 5(\text{mod } 8)$ and show that p must be prime in $Z[\sqrt{2}]$. If p composite in $Z[\sqrt{2}]$ then p has a factorization $p = \alpha\beta$ with $|N(\alpha)| > 1$ and $|N(\beta)| > 1$. Taking the norm of both sides we get $p^2 = N(\alpha)N(\beta)$. It is not possible for p^2 to divide $N(\alpha)$ or $N(\beta)$ since this would imply $|N(\beta)| = 1$, $|N(\alpha)| = 1$ respectively. Hence $|N(\alpha)| = p$ and $|N(\beta)| = p$. From the former we get p=$\pm N(\alpha) = \pm(x^2 - 2y^2)$ for some $x, y \in Z$. Thus $p \equiv 0, 1, 2, 6, 7$ (mod 8) which is a contradiction. ■

Now we assume that p is prime in $Z[\sqrt{2}]$ and show that $p \equiv 3, 5(\text{mod } 8)$. If $p \equiv 1, 7(\text{mod } 8)$ then the equation $x^2 \equiv 2(\text{mod } p)$ has a solution. Hence $x^2 - 2 = kp$. Factoring in $Z[\sqrt{2}]$ we get $(x + \sqrt{2})(x - \sqrt{2}) = kp$. Since p is prime, it must divide one of the factors and by conjugation it divides both. Therefore p divides their difference: $p \mid 2\sqrt{2}$. This is impossible since p is odd and rational. ■

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