

Polygonal Number Theorem

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Abstract

We formalize the proofs of Cauchy's and Legendre's Polygonal Number Theorems given in Melvyn B. Nathanson's book 'Additive Number Theory: The Classical Bases' [2].

For $m \geq 1$, the k -th polygonal number of order $m + 2$ is defined to be $p_m(k) = \frac{mk(k-1)}{2} + k$. The theorems state that:

- If $m \geq 4$ and $N \geq 108m$, then N can be written as the sum of $m + 1$ polygonal numbers of order $m + 2$, at most four of which are different from 0 or 1. If $N \geq 324$, then N can be written as the sum of five pentagonal numbers, at least one of which is 0 or 1.
- Let $m \geq 3$ and $N \geq 28m^3$. If m is odd, then N is the sum of four polygonal numbers of order $m + 2$. If m is even, then N is the sum of five polygonal numbers of order $m + 2$, at least one of which is 0 or 1.

We also formalize the proof of Gauss's theorem which states that every non-negative integer is the sum of three triangular numbers.

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1 Technical Lemmas

We show three lemmas used in the proof of both main theorems.

```
theory Polygonal-Number-Theorem-Lemmas
  imports Three-Squares.Three-Squares
```

```
begin
```

1.1 Lemma 1.10 in [2]

This lemma is split into two parts. We modify the proof given in [2] slightly as we require the second result to hold for $l = 2$ in the proof of Legendre's polygonal number theorem.

theorem *interval-length-greater-than-four*:

```
fixes m N L :: real
assumes m ≥ 3
assumes N ≥ 2*m
assumes L = (2/3 + sqrt (8*N/m - 8)) - (1/2 + sqrt (6*N/m - 3))
shows N ≥ 108*m ⇒ L > 4
```

proof –

```
assume asm: N ≥ 108*m
```

```
show L > 4
```

proof –

```
define x :: real where x = N / m
```

```
define l :: real where l = 4
```

```
define l-0 :: real where l-0 = 4 - 1/6
```

```
have 0: x ≥ 2 unfolding x-def using assms(2)
```

```
by (metis assms(1) divide-right-mono dual-order.trans linorder-le-cases
mult.commute mult-1 nonzero-mult-div-cancel-left numeral-le-one-iff semiring-norm(70)
zero-le-square)
```

```
have 1: L = sqrt (8*x - 8) - sqrt (6*x - 3) + 1/6 by (auto simp add:
x-def assms(3))
```

```
hence 2: L > l ⇔ sqrt (8*x - 8) > sqrt (6*x - 3) + l-0 unfolding
l-0-def l-def by auto
```

```
have 3: sqrt (8*x - 8) > sqrt (6*x - 3) + l-0 ⇔ 2*x - l-0^2 - 5 >
2*l-0 * sqrt (6*x - 3)
```

proof

```
assume sqrt (8*x - 8) > sqrt (6*x - 3) + l-0
```

```
hence (sqrt (8*x - 8))^2 > (sqrt (6*x - 3) + l-0)^2
```

```
using l-0-def asm by (smt (verit, ccfv-SIG) 0 divide-less-eq-1-pos one-power2
pos2 power-mono-iff real-less-rsqrt)
```

```
hence 8*x - 8 > 6*x - 3 + l-0^2 + 2*l-0* sqrt (6*x - 3)
```

```
by (smt (verit, del-insts) 0 power2-sum real-sqrt-pow2-iff)
```

```
thus 2*x - l-0^2 - 5 > 2*l-0* sqrt (6*x - 3) by auto
```

next

```
assume 2*x - l-0^2 - 5 > 2*l-0* sqrt (6*x - 3)
```

```
hence 8*x - 8 > 6*x - 3 + l-0^2 + 2*l-0* sqrt (6*x - 3) by auto
```

```

hence (sqrt (8*x - 8))^2 > (sqrt (6*x - 3) + l-0)^2
  by (smt (verit, best) 0 power2-sum real-sqrt-pow2-iff)
thus sqrt (8*x - 8) > sqrt (6*x - 3) + l-0
  using 0 real-less-rsqrt by force
qed
have 2*x - l-0^2 - 5 > 2*l-0* sqrt (6*x - 3)  $\iff$  4*x*(x - (7*l-0^2 +
5)) + (l-0^2 + 5)^2 + 12*l-0^2 > 0
proof
  assume 2*x - l-0^2 - 5 > 2*l-0* sqrt (6*x - 3)
  hence (2*x - l-0^2 - 5)^2 > (2*l-0* sqrt (6*x - 3))^2
    by (smt (verit, del-insts) 0 asm l-0-def le-divide-eq-1-pos less-1-mult
one-power2 pos2 power-mono-iff sqrt-le-D)
  thus 4*x*(x - (7*l-0^2 + 5)) + (l-0^2 + 5)^2 + 12*l-0^2 > 0
    using 0 by (simp add: algebra-simps power2-eq-square power4-eq-xxxx)
next
  assume 4*x*(x - (7*l-0^2 + 5)) + (l-0^2 + 5)^2 + 12*l-0^2 > 0
  hence (2*x - l-0^2 - 5)^2 > (2*l-0* sqrt (6*x - 3))^2
    using 0 by (simp add: algebra-simps power2-eq-square power4-eq-xxxx)
  from assms(1) have m > 0 by auto
  hence 2*x  $\geq$  2*108
    using x-def asm by (simp add: le-divide-eq)
  hence 2*x - l-0^2 - 5  $\geq$  2*108 - (4-1/6)*(4-1/6) - 5 unfolding
l-0-def by (auto simp add: power2-eq-square)
  hence 2*x - l-0^2 - 5 > 0 by auto
  thus 2*x - l-0^2 - 5 > 2*l-0* sqrt (6*x - 3)
    using  $\langle$ (2*x - l-0^2 - 5)^2 > (2*l-0* sqrt (6*x - 3))^2 $\rangle$  using
power2-less-imp-less by fastforce
qed
from assms(1) have m > 0 by auto
hence x  $\geq$  108 using x-def asm by (simp add: le-divide-eq)
have 7*(4-1/6)*(4-1/6) + 5 < (108::real) by simp
hence 7*l-0^2 + 5 < 108 unfolding l-0-def by (auto simp add: power2-eq-square)
hence x  $\geq$  7*l-0^2 + 5 using  $\langle$ 108  $\leq$  x $\rangle$  by auto
hence 4*x*(x - (7*l-0^2 + 5)) + (l-0^2 + 5)^2 + 12*l-0^2 > 0
  by (smt (verit) mult-nonneg-nonneg power2-less-eq-zero-iff zero-le-power2)
thus ?thesis
  using 2 3  $\langle$ (2 * l-0 * sqrt (6 * x - 3) < 2 * x - l-0^2 - 5) = (0 < 4 * x
* (x - (7 * l-0^2 + 5)) + (l-0^2 + 5)^2 + 12 * l-0^2) $\rangle$  l-def by blast
qed
qed

```

theorem *interval-length-greater-than-lm:*

```

fixes m N :: real
fixes L l :: real
assumes m  $\geq$  3
assumes N  $\geq$  2*m
assumes L = (2/3 + sqrt (8*N/m - 8)) - (1/2 + sqrt (6*N/m - 3))
shows l  $\geq$  2  $\wedge$  N  $\geq$  7*l^2*m^3  $\implies$  L > l*m

```

```

proof –
  assume asm:  $l \geq 2 \wedge N \geq 7 * l^2 * m^3$ 
  show  $L > l * m$ 
  proof –
    from asm have asm1:  $l \geq 2$  and asm2:  $N \geq 7 * l^2 * m^3$  by auto
    define x :: real where  $x = N / m$ 
    define l-0 :: real where  $l-0 = l * m - 1 / 6$ 
    have  $l-0 > 0$  using l-0-def asm1 assms(1)
    by (smt (verit, ccfv-threshold) le-divide-eq-1 mult-le-cancel-left2 of-int-le-1-iff)
    have  $0: x \geq 2$  using x-def assms(1,2) by (simp add: pos-le-divide-eq)
    have  $1: L = \text{sqrt}(8 * x - 8) - \text{sqrt}(6 * x - 3) + 1 / 6$  by (auto simp add: x-def
assms(3))
    hence  $2: L > l * m \iff \text{sqrt}(8 * x - 8) > \text{sqrt}(6 * x - 3) + l-0$  by (auto simp
add: l-0-def)
    have  $3: \text{sqrt}(8 * x - 8) > \text{sqrt}(6 * x - 3) + l-0 \iff 2 * x - l-0^2 - 5 > 2 * l-0$ 
 $* \text{sqrt}(6 * x - 3)$ 
    proof
      assume  $\text{sqrt}(8 * x - 8) > \text{sqrt}(6 * x - 3) + l-0$ 
      hence  $(\text{sqrt}(8 * x - 8))^2 > (\text{sqrt}(6 * x - 3) + l-0)^2$ 
      using l-0-def asm1 by (smt (verit, best)  $\langle 0 < l-0 \rangle$  real-le-lsqr real-sqrt-four
real-sqrt-less-iff real-sqrt-pow2-iff)
      hence  $8 * x - 8 > 6 * x - 3 + l-0^2 + 2 * l-0 * \text{sqrt}(6 * x - 3)$ 
      by (smt (verit, del-insts)  $0$  power2-sum real-sqrt-pow2-iff)
      thus  $2 * x - l-0^2 - 5 > 2 * l-0 * \text{sqrt}(6 * x - 3)$  by auto
    next
      assume  $2 * x - l-0^2 - 5 > 2 * l-0 * \text{sqrt}(6 * x - 3)$ 
      hence  $8 * x - 8 > 6 * x - 3 + l-0^2 + 2 * l-0 * \text{sqrt}(6 * x - 3)$  by auto
      hence  $(\text{sqrt}(8 * x - 8))^2 > (\text{sqrt}(6 * x - 3) + l-0)^2$ 
      by (smt (verit, del-insts)  $0$  power2-sum real-sqrt-pow2-iff)
      thus  $\text{sqrt}(8 * x - 8) > \text{sqrt}(6 * x - 3) + l-0$ 
      using  $0$  real-less-rsqrt by force
    qed
    have  $2 * x - l-0^2 - 5 > 2 * l-0 * \text{sqrt}(6 * x - 3) \iff 4 * x * (x - (7 * l-0^2 +$ 
 $5)) + (l-0^2 + 5)^2 + 12 * l-0^2 > 0$ 
    proof
      assume  $2 * x - l-0^2 - 5 > 2 * l-0 * \text{sqrt}(6 * x - 3)$ 
      have  $(2 * x - l-0^2 - 5)^2 > (2 * l-0 * \text{sqrt}(6 * x - 3))^2$ 
      using  $\langle 0 < l-0 \rangle$  by (smt (verit, ccfv-SIG)  $0 \langle 2 * l-0 * \text{sqrt}(6 * x - 3) <$ 
 $2 * x - l-0^2 - 5 \rangle$  pos2 power-strict-mono real-sqrt-ge-zero zero-le-mult-iff)
      thus  $4 * x * (x - (7 * l-0^2 + 5)) + (l-0^2 + 5)^2 + 12 * l-0^2 > 0$ 
      using  $0$  by (simp add: algebra-simps power2-eq-square power4-eq-xxxx)
    next
      assume  $4 * x * (x - (7 * l-0^2 + 5)) + (l-0^2 + 5)^2 + 12 * l-0^2 > 0$ 
      hence  $(2 * x - l-0^2 - 5)^2 > (2 * l-0 * \text{sqrt}(6 * x - 3))^2$ 
      using  $0$  by (simp add: algebra-simps power2-eq-square power4-eq-xxxx)
      have  $m > 0$  using assms(1) by simp
      hence  $x \geq 7 * l^2 * m^2$ 
      unfolding x-def using asm2 assms(1)
      by (simp add: mult-imp-le-div-pos power2-eq-square power3-eq-cube)

```

hence $4: 2*x - l-0^2 - 5 \geq 14*l^2*m^2 - (l*m-1/6)^2 - 5$
by (*simp add: x-def l-0-def power2-eq-square*)
have $(l*m-(1/6::real))^2 = (l*m)^2 - l*m/3 + (1/36::real)$
apply (*simp add: power2-eq-square*)
by *argo*
hence $14*l^2*m^2 - (l*m-1/6)^2 - 5 = 14*l^2*m^2 - l^2*m^2 + l*m/3 - 1/36 - 5$
using 4 **by** (*auto simp add: power2-eq-square*)
hence $14*l^2*m^2 - l^2*m^2 + l*m/3 - 1/36 - 5 = 13*l^2*m^2 + l*m/3 - 1/36 - 5$ **by** *argo*
from *asm1* *assms(1)* **have** $5: l*m/3 > 0$ **by** *simp*
have $l > 0$ **using** *asm1* **by** *auto*
hence $l*m \geq 2*2$ **using** *asm1* *mult-mono'* *zero-le-numeral* **by** *blast*
have $m > 0$ **using** *assms(1)* **by** *auto*
hence $m*m \geq 3*3$
by (*metis* *assms(1)* *less-eq-real-def* *mult-le-less-imp-less* *zero-less-numeral*)
hence $13*m*m - 1 \geq 13*3*3-1$ **by** *simp*
have $3*3 > (0::real)$ **by** *auto*
hence $13*l*l*m*m \geq (13::real)*2*2*3*3$ **using** $\langle l*m \geq 2*2 \rangle$ *asm1*
by (*meson* $\langle 0 < l \rangle \langle 0 < m \rangle$ *assms(1)* *less-eq-real-def* *mult-mono* *split-mult-pos-le* *zero-le-numeral*)
hence $13*l^2*m^2 + l*m/3 - 1/36 - 5 \geq 13*2*2*3*3-1/36-(5::real)$
using 5 **by** (*auto simp add: power2-eq-square*)
have $13*3*3*3*3-1/36-(5::real) > 0$ **by** *auto*
hence $2*x - l-0^2 - 5 > 0$
using 4 $\langle 13 * 2 * 2 * 3 * 3 - 1 / 36 - 5 \leq 13 * l^2 * m^2 + l * m / 3 - 1 / 36 - 5 \rangle$ $\langle 14 * l^2 * m^2 - (l * m - 1 / 6)^2 - 5 = 14 * l^2 * m^2 - l^2 * m^2 + l * m / 3 - 1 / 36 - 5 \rangle$ **by** *force*
thus $2*x - l-0^2 - 5 > 2*l-0 * \text{sqrt}(6*x - 3)$
by (*smt* (*verit*) $\langle (2 * l-0 * \text{sqrt}(6 * x - 3))^2 < (2 * x - l-0^2 - 5)^2 \rangle$, *power-mono*)
qed
have $(1/6)^2 * (36::real) = 1$ **by** (*auto simp add: power2-eq-square*)
from *assms(1)* **have** $m > 0$ **by** *auto*
hence $x \geq 7*l^2*m^2$ **unfolding** *x-def* **using** *asm2*
by (*simp add: pos-le-divide-eq power2-eq-square power3-eq-cube*)
from *asm1* **have** $l > 0$ **by** *auto*
from *assms(1)* *asm1* $\langle m > 0 \rangle \langle l > 0 \rangle$ **have** $l*m \geq 2*(3::real)$
by (*metis* *mult-less-cancel-right* *mult-mono* *verit-comp-simplify1* (1) *verit-comp-simplify1* (3) *zero-le-numeral*)
hence $-2*7*l*m/6 + 7*(1/6)*(1/6) + 5 < (0::real)$ **by** *simp*
hence $7*l^2*m^2 > 7*l-0^2 + (5::real)$ **unfolding** *l-0-def*
apply (*auto simp add: power2-eq-square*)
by *argo*
hence $x \geq 7*l-0^2 + 5$
using $\langle 7 * l^2 * m^2 \leq x \rangle$ **by** *linarith*
hence $4*x*(x - (7*l-0^2 + 5)) + (l-0^2 + 5)^2 + 12*l-0^2 > 0$
by (*smt* (*verit*) *mult-nonneg-nonneg* *power2-less-eq-zero-iff* *zero-le-power2*)
thus *?thesis*

using $2/3 \langle (2 * l - 0 * \text{sqrt}(6 * x - 3) < 2 * x - l - 0^2 - 5) = (0 < 4 * x * (x - (7 * l - 0^2 + 5)) + (l - 0^2 + 5)^2 + 12 * l - 0^2) \rangle$ **by** *fastforce*
qed
qed

lemmas *interval-length-greater-than-2m* [*simp*] = *interval-length-greater-than-lm*
[where $l=2$, *simplified***]**

1.2 Lemma 1.11 in [2]

We show Lemma 1.11 in [2] which is also known as Cauchy's Lemma.

theorem *Cauchy-lemma*:

fixes $m N a b r :: \text{real}$
assumes $m \geq 3 \ N \geq 2 * m$
and $0 \leq a \ 0 \leq b \ 0 \leq r \ r < m$
and $N = m * (a - b) / 2 + b + r$
and $1/2 + \text{sqrt}(6 * N / m - 3) \leq b \wedge b \leq 2/3 + \text{sqrt}(8 * N / m - 8)$
shows $b^{\wedge}2 < 4 * a \wedge 3 * a < b^{\wedge}2 + 2 * b + 4$

proof –

from *assms* **have** *asm1*: $1/2 + \text{sqrt}(6 * N / m - 3) \leq b$ **and** *asm2*: $b \leq 2/3 + \text{sqrt}(8 * N / m - 8)$ **by** *auto*

have $N - b - r = m * (a - b) / 2$ **using** *assms(7)* **by** *simp*
hence $a = (N - b - r) * 2 / m + b$ **using** *assms(1)* **by** *simp*
hence $a = b - 2/m * b + 2 * (N - r) / m$

apply (*simp add: algebra-simps*)
by (*smt (verit, del-Insts) add-divide-distrib*)

hence $a = b * (1 - 2/m) + 2 * (N - r) / m$

by (*simp add: right-diff-distrib'*)

have $b^{\wedge}2 < 4 * a$

proof –

from a **have** 0 : $b^{\wedge}2 - 4 * a = b^{\wedge}2 - 4 * (1 - 2/m) * b - 8 * (N - r) / m$ **by** *simp*

have $3/m \leq 1$ **using** *assms(1)* **by** *simp*

hence 1 : $2/3 \leq 2 * (1 - 2/m)$ **by** *simp*

have $N/m - 1 < N/m - r/m$ **using** *assms(1,6)* **by** *simp*

hence $\text{sqrt}(8 * (N/m - 1)) < \text{sqrt}(8 * ((N - r) / m))$ **by** (*simp add: diff-divide-distrib*)

hence 2 : $\text{sqrt}(8 * N / m - 8) < \text{sqrt}(8 * ((N - r) / m))$ **by** *simp*

have $2/3 + \text{sqrt}(8 * N / m - 8) < 2 * (1 - 2/m) + \text{sqrt}(8 * ((N - r) / m))$

using $1 \ 2$ **by** *linarith*

hence $b < 2 * (1 - 2/m) + \text{sqrt}(8 * (N - r) / m)$ **using** *asm2* **by** *simp*

hence 3 : $b < 2 * (1 - 2/m) + \text{sqrt}(4 * (1 - 2/m)^{\wedge}2 + 8 * (N - r) / m)$

by (*smt (verit, best) power2-less-0 real-sqrt-le-iff*)

define $r1$ **where** $r1 = 2 * (1 - 2/m) - \text{sqrt}(4 * (1 - 2/m)^{\wedge}2 + 8 * (N - r) / m)$

define $r2$ **where** $r2 = 2 * (1 - 2/m) + \text{sqrt}(4 * (1 - 2/m)^{\wedge}2 + 8 * (N - r) / m)$

have $r1 * r2 = (2 * (1 - 2/m) - \text{sqrt}(4 * (1 - 2/m)^{\wedge}2 + 8 * (N - r) / m)) * (2 * (1 - 2/m) + \text{sqrt}(4 * (1 - 2/m)^{\wedge}2 + 8 * (N - r) / m))$

using *r1-def r2-def* **by** *simp*

hence $r1 * r2 = 2 * (1 - 2/m) * (2 * (1 - 2/m) + \text{sqrt}(4 * (1 - 2/m)^{\wedge}2 + 8 * (N - r) / m))$

$r)/m)) -$
 $\text{sqrt } (4*(1-2/m)^2 + 8*(N - r)/m)*(2*(1-2/m) + \text{sqrt } (4*(1-2/m)^2 + 8*(N - r)/m))$
by (*simp add: Rings.ring-distrib*(3))
hence $r1*r2 = (2*(1-2/m))^2 + 2*(1-2/m)* \text{sqrt } (4*(1-2/m)^2 + 8*(N - r)/m) - 2*(1-2/m)* \text{sqrt } (4*(1-2/m)^2 + 8*(N - r)/m)$
 $- (\text{sqrt } (4*(1-2/m)^2 + 8*(N - r)/m))^2$ **by** (*simp add: distrib-left power2-eq-square*)
hence $r1*r2 = (2*(1-2/m))^2 - (\text{sqrt } (4*(1-2/m)^2 + 8*(N - r)/m))^2$
by *simp*

hence $r1 * r2 = 4*(1-2/m)^2 - 4*(1-2/m)^2 - 8*(N - r)/m$
using *assms*(1) *assms*(2) *assms*(6) *four-x-squared*
by (*smt (verit) divide-nonneg-nonneg real-sqrt-pow2-iff zero-compare-simps*(12))
hence $r1\text{-times-}r2:r1*r2 = -8*(N-r)/m$ **by** *linarith*

have $(b-r1)*(b-r2) = b*(b-r2) - r1*(b-r2)$ **using** *cross3-simps*(28) **by** *blast*
hence $(b-r1)*(b-r2) = b^2 - b*r2 - b*r1 + r1*r2$ **by** (*simp add: power2-eq-square right-diff-distrib*)
hence $(b-r1)*(b-r2) = b^2 - b*(2*(1-2/m) + \text{sqrt } (4*(1-2/m)^2 + 8*(N - r)/m)) - b*(2*(1-2/m) - \text{sqrt } (4*(1-2/m)^2 + 8*(N - r)/m)) + r1*r2$
using *r1-def r2-def* **by** *simp*
hence $(b-r1)*(b-r2) = b^2 - b*2*(1-2/m) - b* \text{sqrt } (4*(1-2/m)^2 + 8*(N - r)/m) - b*(2*(1-2/m) - \text{sqrt } (4*(1-2/m)^2 + 8*(N - r)/m)) + r1*r2$
by (*simp add: distrib-left*)
hence $(b-r1)*(b-r2) = b^2 - b*2*(1-2/m) - b* \text{sqrt } (4*(1-2/m)^2 + 8*(N - r)/m) - b*2*(1-2/m) + b* \text{sqrt } (4*(1-2/m)^2 + 8*(N - r)/m) + r1*r2$
by (*simp add: Rings.ring-distrib*(4))
hence $(b-r1)*(b-r2) = b^2 - b*4*(1-2/m) + r1*r2$ **by** *simp*
hence $(b-r1)*(b-r2) = b^2 - 4*(1 - 2/m)*b - 8*(N-r)/m$ **using** *r1-times-r2*
by (*simp add: <r1 * r2 = 4 * (1 - 2 / m)^2 - 4 * (1 - 2 / m)^2 - 8 * (N - r) / m>*)
hence $b^2 - 4*(1 - 2/m)*b - 8*(N-r)/m < 0$ **using** 3 *assms*(4)
by (*smt (verit, del-insts) <r1 * r2 = 4 * (1 - 2 / m)^2 - 4 * (1 - 2 / m)^2 - 8 * (N - r) / m> assms*(1) *assms*(2) *assms*(6) *divide-pos-pos mult-nonneg-nonneg mult-pos-neg r2-def*)
thus *?thesis* **using** 0 **by** *simp*
qed
have $3*a < b^2 + 2*b + 4$
proof -
from *a* **have** 4: $b^2 + 2*b + 4 - 3*a = b^2 - (1-6/m)*b - (6*(N-r)/m - 4)$ **by** *argo*
have 5: $1/2 > 1/2 - 3/m$ **using** *assms*(1) **by** *simp*
hence $1/2 - 3/m < 1$ **by** *linarith*
also **have** $1/2 - 3/m > -1$ **using** *assms*(1)
by (*smt (verit) divide-le-0-1-iff less-divide-eq-1-pos*)
hence $(1/2 - 3/m)^2 < 1$
by (*metis (no-types, opaque-lifting) calculation less-eq-real-def power2-eq-1-iff square-le-1 verit-comp-simplify1*(3))

hence 6: $\text{sqrt}(6*N/m - 3) > \text{sqrt}((1/2 - 3/m)^2 + 6*N/m - 4)$ **using** *assms(1)* **by** *simp*
from *asm1 5 6* **have** $b > (1/2 - 3/m) + \text{sqrt}((1/2 - 3/m)^2 + 6*N/m - 4)$ **by** *linarith*
hence 7: $b > (1/2 - 3/m) + \text{sqrt}((1/2 - 3/m)^2 + 6*(N - r)/m - 4)$
by (*smt (verit, ccfv-SIG) assms(1) assms(5) divide-right-mono real-sqrt-le-mono*)
define *s1* **where** $s1 = (1/2 - 3/m) - \text{sqrt}((1/2 - 3/m)^2 + 6*(N - r)/m - 4)$
define *s2* **where** $s2 = (1/2 - 3/m) + \text{sqrt}((1/2 - 3/m)^2 + 6*(N - r)/m - 4)$
have $s1 * s2 = (1/2 - 3/m) * ((1/2 - 3/m) + \text{sqrt}((1/2 - 3/m)^2 + 6*(N - r)/m - 4)) - \text{sqrt}((1/2 - 3/m)^2 + 6*(N - r)/m - 4) * ((1/2 - 3/m) + \text{sqrt}((1/2 - 3/m)^2 + 6*(N - r)/m - 4))$
using *s1-def s2-def Rings.ring-distrib(3)* **by** *blast*
hence $s1 * s2 = (1/2 - 3/m)^2 + (1/2 - 3/m) * \text{sqrt}((1/2 - 3/m)^2 + 6*(N - r)/m - 4) - \text{sqrt}((1/2 - 3/m)^2 + 6*(N - r)/m - 4) * ((1/2 - 3/m) + \text{sqrt}((1/2 - 3/m)^2 + 6*(N - r)/m - 4))$
by (*simp add: nat-distrib(2) power2-eq-square*)
hence $s1 * s2 = (1/2 - 3/m)^2 + (1/2 - 3/m) * \text{sqrt}((1/2 - 3/m)^2 + 6*(N - r)/m - 4) - (1/2 - 3/m) * \text{sqrt}((1/2 - 3/m)^2 + 6*(N - r)/m - 4) - (\text{sqrt}((1/2 - 3/m)^2 + 6*(N - r)/m - 4))^2$
by (*smt (verit, ccfv-SIG) Groups.mult-ac(2) Rings.ring-distrib(3) power2-eq-square*)
hence 8: $s1 * s2 = (1/2 - 3/m)^2 - (\text{sqrt}((1/2 - 3/m)^2 + 6*(N - r)/m - 4))^2$ **by** *simp*
from *assms(1,6)* **have** $-r/m > -1$ **by** *simp*
hence $-6*r/m > -6$ **by** *simp*
hence $12 - 4 - 6*r/m > 0$ **by** *simp*
hence $12*m/m - 6*r/m - 4 > 0$ **using** *assms(1)* **by** *simp*
hence $6*(2*m - r)/m - 4 > 0$ **by** *argo*
hence $6*(N - r)/m - 4 > 0$ **using** *assms(1,2)*
by (*smt (verit, best) divide-right-mono*)
hence $s1 * s2 = (1/2 - 3/m)^2 - (1/2 - 3/m)^2 - 6*(N - r)/m + 4$
using *8*
by (*smt (verit) real-sqrt-pow2-iff zero-le-power2*)

have $(b - s1) * (b - s2) = b * (b - s2) - s1 * (b - s2)$ **using** *cross3-simps(28)* **by** *blast*

hence $(b - s1) * (b - s2) = b^2 - b * s2 - b * s1 + s1 * s2$ **by** (*simp add: power2-eq-square right-diff-distrib*)

hence $(b - s1) * (b - s2) = b^2 - b * ((1/2 - 3/m) + \text{sqrt}((1/2 - 3/m)^2 + 6*(N - r)/m - 4)) - b * ((1/2 - 3/m) - \text{sqrt}((1/2 - 3/m)^2 + 6*(N - r)/m - 4))$

+ s1 * s2 using s1-def s2-def by simp

hence $(b - s1) * (b - s2) = b^2 - b * (1/2 - 3/m) - b * \text{sqrt}((1/2 - 3/m)^2 + 6*(N - r)/m - 4) - b * ((1/2 - 3/m) - \text{sqrt}((1/2 - 3/m)^2 + 6*(N - r)/m - 4))$

+ s1 * s2 by (simp add: nat-distrib(2))
 hence (b-s1)*(b-s2) = b²-b*(1/2 - 3/m)-b* sqrt ((1/2 - 3/m)²
 + 6*(N - r)/m - 4)-b*(1/2 - 3/m)+b* sqrt ((1/2 - 3/m)² + 6*(N -
 r)/m-4)+s1 * s2
 by (smt (verit, ccfv-SIG) nat-distrib(2))
 hence (b-s1)*(b-s2) = b²-2*b*(1/2 - 3/m)+s1 * s2 by simp
 hence (b-s1)*(b-s2) = b²-2*b*(1/2 - 3/m)+ (1/2 - 3/m)² - (1/2
 - 3/m)² - 6*(N - r)/m + 4
 using ⟨s1 * s2 = (1 / 2 - 3 / m)² - (1 / 2 - 3 / m)² - 6 * (N - r) /
 m + 4⟩ by fastforce
 hence (b-s1)*(b-s2) = b²-2*b*(1/2-3/m)- 6*(N - r)/m + 4 by simp
 hence (b-s1)*(b-s2) = b²-b*(1-6/m)- 6*(N - r)/m + 4 by simp
 hence (b-s1)*(b-s2) = b²-b*(1-6/m)- (6*(N - r)/m - 4) by simp
 hence b² - (1-6/m)*b - (6*(N-r)/m - 4) > 0 using 7 by (smt (verit,
 del-insts) 8 Groups.mult-ac(2)
 ⟨s1 * s2 = (1 / 2 - 3 / m)² - (1 / 2 - 3 / m)² - 6 * (N - r) / m + 4⟩
 real-sqrt-ge-0-iff s1-def s2-def zero-compare-simps(8) zero-le-power2)
 thus ?thesis using 4 by simp
 qed
 show ?thesis by (simp add: ⟨3 * a < b² + 2 * b + 4⟩ ⟨b² < 4 * a⟩)
 qed

lemmas Cauchy-lemma-r-eq-zero = Cauchy-lemma [where r=0, simplified]

1.3 Lemma 1.12 in [2]

lemma not-one:

fixes a b :: nat
 assumes a ≥ 1
 assumes b ≥ 1
 assumes ∃ k1 :: nat. a = 2*k1+1
 assumes ∃ k2 :: nat. b = 2*k2+1
 assumes b² < 4*a
 shows 4*a-b² ≠ 1

proof

assume 4*a-b² = 1
 hence b² = 4*a-1 by auto
 hence b² mod 4 = (4*a-1) mod 4 by auto
 have (4*a-1) mod 4 = 3 mod 4 using assms(1) by (simp add: mod-diff-eq-nat)
 hence b² mod 4 = 3 using ⟨b² = 4*a-1⟩ mod-less by presburger
 thus False using assms by (metis One-nat-def eq-numeral-Suc insert-iff nat.simps(3)
 power-two-mod-four pred-numeral-simps(3) singletonD)
 qed

lemma not-two:

fixes a b :: nat
 assumes a ≥ 1

assumes $b \geq 1$
assumes $\exists k1 :: \text{nat}. a = 2*k1 + 1$
assumes $1: \exists k2 :: \text{nat}. b = 2*k2 + 1$
assumes $b^2 < 4*a$
shows $4*a - b^2 \neq 2$

proof

assume $4*a - b^2 = 2$
hence $b^2 = 4*a - 2$ **by** *auto*
from 1 **have** $2: \neg 2 \text{ dvd } b^2$ **by** *auto*
have $2 \text{ dvd } (4*a - 2)$ **by** *auto*
thus *False* **using** $\langle b^2 = 4*a - 2 \rangle 2$ **by** *auto*

qed

The following lemma shows that given odd positive integers x, y, z and b , where $x \geq y \geq z$, we may pick a suitable integer u where $u = z$ or $u = -z$, such that $b + x + y + u \equiv 0 \pmod{4}$.

lemma *suit-z*:

fixes $b\ x\ y\ z :: \text{nat}$
assumes $\text{odd } b \wedge \text{odd } x \wedge \text{odd } y \wedge \text{odd } z$
assumes $x \geq y \wedge y \geq z$
shows $\exists u :: \text{int}. (u = z \vee u = -z) \wedge (b + x + y + u) \bmod 4 = 0$

proof –

from *assms* **have** $0: (b + x + y) \bmod 4 = 1 \vee (b + x + y) \bmod 4 = 3$ **by** (*metis dvd-refl even-add*)

even-even-mod-4-iff landau-product-preprocess(53) mod-exhaust-less-4)

from *assms* **have** $1: z \bmod 4 = 1 \vee z \bmod 4 = 3$ **by** (*metis dvd-0-right dvd-refl even-even-mod-4-iff mod-exhaust-less-4*)

have $c1: \exists u1 :: \text{int}. (u1 = z \vee u1 = -z) \wedge (b + x + y + u1) \bmod 4 = 0$

if *asm1*: $(b + x + y) \bmod 4 = 1 \wedge z \bmod 4 = 3$

proof –

from *asm1* **have** $2: (b + x + y + z) \bmod 4 = 0$ **by** (*metis add-num-simps(1) add-num-simps(7)*)

mod-add-eq mod-self numeral-plus-one one-plus-numeral-commute)

define $u1 :: \text{int}$ **where** $u1 = z$

show $\exists u1 :: \text{int}. (u1 = z \vee u1 = -z) \wedge (b + x + y + u1) \bmod 4 = 0$ **using** 2 *u1-def*

by (*metis Num.of-nat-simps(4) of-nat-0 of-nat-numeral zmod-int*)

qed

have $c2: \exists u2 :: \text{int}. (u2 = z \vee u2 = -z) \wedge (b + x + y + u2) \bmod 4 = 0$

if *asm2*: $(b + x + y) \bmod 4 = 1 \wedge z \bmod 4 = 1$

proof –

from *asm2* **have** $3: (b + x + y - z) \bmod 4 = 0$

by (*metis assms(2) mod-eq-0-iff-dvd mod-eq-dvd-iff-nat trans-le-add2*)

define $u2 :: \text{int}$ **where** $u2 = -z$

show $\exists u2 :: \text{int}. (u2 = z \vee u2 = -z) \wedge (b + x + y + u2) \bmod 4 = 0$ **using** 3 *u2-def*

by (*metis Num.of-nat-simps(2) asm2 mod-0*)

```

mod-add-cong more-arith-simps(4) of-nat-numeral zmod-int)
qed

have c3:∃ u3::int.(u3=z ∨ u3=-z) ∧ (b+x+y+u3) mod 4 = 0
  if asm3:(b+x+y) mod 4 = 3 ∧ z mod 4 = 1
proof -
  from asm3 have 4: (b+x+y+z) mod 4 = 0 by (metis add-num-simps(1)
add-num-simps(7)
mod-add-eq mod-self numeral-plus-one)
  define u3::int where u3=z
  show ∃ u3::int.(u3=z ∨ u3=-z) ∧ (b+x+y+u3) mod 4 = 0 using 4 u3-def
  by (metis Num.of-nat-simps(4) of-nat-0 of-nat-numeral zmod-int)
qed

have c4:∃ u4::int.(u4=z ∨ u4=-z) ∧ (b+x+y+u4) mod 4 = 0
  if asm4:(b+x+y) mod 4 = 3 ∧ z mod 4 = 3
proof -
  from asm4 have 5: (b+x+y-z) mod 4 = 0
  by (metis assms(2) mod-eq-0-iff-dvd mod-eq-dvd-iff-nat trans-le-add2)
  define u4::int where u4=-z
  show ∃ u4::int.(u4=z ∨ u4=-z) ∧ (b+x+y+u4) mod 4 = 0 using 5 u4-def
by (metis asm4 mod-0
mod-add-cong more-arith-simps(4) of-nat-numeral zmod-int)
qed

show ?thesis using assms 0 1 c1 c2 c3 c4 by auto
qed

lemma four-terms-bin-exp-allsum:
  fixes b s t u v :: int
  assumes b = s+t+u+v
  shows b2 = t2+u2+s2+v2+2*t*u+2 * s * v + 2*t * s + 2*t * v +2*u
* s +2*u * v

proof -
  from assms have b2 = (t+u)2+(s+v)2+2*(t+u)*(s+v) by (smt (verit,
best) power2-sum)
  hence b-simp1:b2 = (t2+u2+2*t*u) + (s2+v2+2 * s * v)+2*(t+u)*(s+v)

  by (simp add: power2-sum)
  have 2*(t+u)*(s+v) = 2*t * s + 2*t * v +2*u * s +2*u * v
  using int-distrib(1) int-distrib(2) by force
  from this b-simp1 have b-expression:b2 = t2+u2+s2+v2+2*t*u+2 * s
* v +
2*t * s + 2*t * v +2*u * s +2*u * v by auto
  thus ?thesis by auto
qed

lemma four-terms-bin-exp-twodiff:

```

fixes $b\ s\ t\ u\ v :: \text{int}$
assumes $b = s+t-u-v$
shows $b^2 = t^2+u^2+s^2+v^2-2*t*u-2*s*v+2*t*s-2*t*v-2*u*s+2*u*v$

proof –

from *assms* **have** $b^2 = (s-u)^2+(t-v)^2+2*(s-u)*(t-v)$ **by** (*smt* (*verit*, *best*) *power2-sum*)
hence *b-simp1*: $b^2 = s^2+u^2-2*s*u+t^2+v^2-2*t*v+2*(s-u)*(t-v)$
by (*simp add*: *power2-diff*)
have $2*(s-u)*(t-v) = 2*s*t-2*s*v-2*u*t+2*u*v$
by (*simp add*: *Rings.ring-distrib(3)* *Rings.ring-distrib(4)*)
from *this b-simp1* **have** *b-expression*: $b^2 = t^2+u^2+s^2+v^2-2*t*u-2*s*v+2*t*s-2*t*v-2*u*s+2*u*v$ **by** *auto*
thus *?thesis* **by** *auto*
qed

If a quadratic with positive leading coefficient is always non-negative, its discriminant is non-positive.

lemma *qua-disc*:

fixes $a\ b\ c :: \text{real}$
assumes $a > 0$
assumes $\forall x :: \text{real}. a*x^2+b*x+c \geq 0$
shows $b^2 - 4*a*c \leq 0$

proof –

from *assms* **have** $0:\forall x :: \text{real}. (a*x^2+b*x+c)/a \geq 0$ **by** *simp*
from *assms* **have** $1:\forall x :: \text{real}. (b*x+c)/a = b/a*x+c/a$ **by** (*simp add*: *add-divide-distrib*)
from *assms* **have** $\forall x :: \text{real}. (a*x^2+b*x+c)/a = x^2+(b*x+c)/a$ **by** (*simp add*: *is-num-normalize(1)*)
from *1 this* **have** $\forall x :: \text{real}. (a*x^2+b*x+c)/a = x^2+b/a*x+c/a$ **by** *simp*
hence *atleastzero*: $\forall x :: \text{real}. x^2+b/a*x+c/a \geq 0$ **using** *0* **by** *simp*

from *assms* **have** $2:\forall x :: \text{real}. x^2+b/a*x+c/a = x^2+2*b/(2*a)*x+c/a+b^2/(4*a^2)-b^2/(4*a^2)$
by *simp*
have *simp1*: $\forall x :: \text{real}. (x+b/(2*a))^2 = x^2+2*b/(2*a)*x+(b/(2*a))^2$ **by** (*simp add*: *power2-sum*)
have $(b/(2*a))^2 = b^2/(4*a^2)$ **by** (*metis four-x-squared power-divide*)
hence $\forall x :: \text{real}. x^2+b/a*x+c/a = (x+b/(2*a))^2+c/a-b^2/(4*a^2)$ **using** *2 simp1* **by** *auto*
hence $\forall x :: \text{real}. (x+b/(2*a))^2+c/a-b^2/(4*a^2) \geq 0$ **using** *atleastzero* **by** *presburger*
hence $3:\forall x :: \text{real}. b^2/(4*a^2)-c/a \leq (x+b/(2*a))^2$ **by** (*smt* (*verit*, *del-insts*))
have $\exists x :: \text{real}. (x+b/(2*a))^2=0$ **by** (*metis diff-add-cancel power-zero-numeral*)
hence $b^2/(4*a^2)-c/a \leq 0$ **using** *3* **by** *metis*
hence $4:4*a^2*(b^2/(4*a^2)-c/a) \leq 0$ **using** *assms* **by** (*simp add*: *mult-nonneg-nonpos*)
have $5:4*a^2*b^2/(4*a^2) = b^2$ **using** *assms* **by** *simp*
have $6:4*a^2*c/a = 4*a*c$ **using** *assms* **by** (*simp add*: *power2-eq-square*)

show *?thesis* **using** 4 5 6 *assms* **by** (*simp add: Rings.ring-distrib(4)*)
qed

The following lemma shows for any point on a 3D sphere with radius a , the sum of its coordinates lies between $\sqrt{3a}$ and $-\sqrt{3a}$.

lemma *three-terms-Cauchy-Schwarz*:

fixes $x\ y\ z\ a :: \text{real}$
assumes $a > 0$
assumes $x^2 + y^2 + z^2 = a$
shows $(x+y+z) \geq -\text{sqrt}(3*a) \wedge (x+y+z) \leq \text{sqrt}(3*a)$

proof –

have $1:\forall t::\text{real}. (t*x+1)^2 = t^2*x^2+1+2*t*x$ **by** (*simp add: power2-sum power-mult-distrib*)

have $2:\forall t::\text{real}. (t*y+1)^2 = t^2*y^2+1+2*t*y$ **by** (*simp add: power2-sum power-mult-distrib*)

have $3:\forall t::\text{real}. (t*z+1)^2 = t^2*z^2+1+2*t*z$ **by** (*simp add: power2-sum power-mult-distrib*)

from 1 2 3 **have** $4:\forall t::\text{real}. (t*x+1)^2 + (t*y+1)^2 + (t*z+1)^2 = t^2*x^2+1+2*t*x + t^2*y^2+1+2*t*y + t^2*z^2+1+2*t*z$ **by** *auto*

have $\forall t::\text{real}. t^2*x^2+t^2*y^2=t^2*(x^2+y^2)$ **by** (*simp add: nat-distrib(2)*)

hence $5:\forall t::\text{real}. t^2*x^2+t^2*y^2+t^2*z^2=t^2*(x^2+y^2+z^2)$ **by** (*metis nat-distrib(2)*)

have $6:\forall t::\text{real}. 2*t*x+2*t*y+2*t*z = t*2*(x+y+z)$ **by** (*simp add: Groups.mult-ac(2) distrib-right*)

from 4 5 6 **have** $\forall t::\text{real}. (t*x+1)^2 + (t*y+1)^2 + (t*z+1)^2 = t^2*(x^2+y^2+z^2) + t*2*(x+y+z) + 3$

by (*smt (verit, best)*)

hence $\forall t::\text{real}. t^2*(x^2+y^2+z^2) + t*2*(x+y+z) + 3 \geq 0$ **by** (*metis add-nonneg-nonneg zero-le-power2*)

hence $(2*(x+y+z))^2 - 12*(x^2+y^2+z^2) \leq 0$ **using** *qua-disc*

by (*smt (z3) power2-diff power2-sum power-zero-numeral sum-squares-bound*)

hence $12*(x^2+y^2+z^2) \geq 4*(x+y+z)^2$ **by** (*simp add: four-x-squared*)

hence $3*a \geq (x+y+z)^2$ **using** *assms* **by** *auto*

thus *?thesis* **by** (*smt (verit, del-insts) real-sqrt-abs real-sqrt-le-iff*)

qed

We adapt the lemma above through changing the types for the convenience of our proof.

lemma *three-terms-Cauchy-Schwarz-nat-ver*:

fixes $x\ y\ z\ a :: \text{nat}$
assumes $a > 0$
assumes $x^2 + y^2 + z^2 = a$
shows $(x+y+z) \geq -\text{sqrt}(3*a) \wedge (x+y+z) \leq \text{sqrt}(3*a)$

proof –

have *fac1*: $\text{real}(x+y+z) = \text{real } x + \text{real } y + \text{real } z$ **by** *auto*

have *fac2*: $3*(\text{real } a) = \text{real}(3*a)$ **by** *auto*
thus *?thesis* **using** *fac1 three-terms-Cauchy-Schwarz fac2* **by** (*smt (verit) assms(1) assms(2) nat-less-real-le of-nat-0-le-iff of-nat-add of-nat-power*)
qed

This theorem is Lemma 1.12 in [2], which shows for odd positive integers a and b satisfying certain properties, there exist four non-negative integers s, t, u and v such that $a = s^2 + t^2 + u^2 + v^2$ and $b = s + t + u + v$. We use the Three Squares Theorem AFP entry [1].

theorem *four-nonneg-int-sum*:

fixes $a\ b :: \text{nat}$
assumes $a \geq 1$
assumes $b \geq 1$
assumes *odd a*
assumes *odd b*
assumes $3*b^2 < 4*a$
assumes $3*a < b^2 + 2*b + 4$
shows $\exists s\ t\ u\ v :: \text{int. } s \geq 0 \wedge t \geq 0 \wedge u \geq 0 \wedge v \geq 0 \wedge a = s^2 + t^2 + u^2 + v^2 \wedge$
 $b = s + t + u + v$

proof –

from *assms* **have** $0 : \exists k1 :: \text{nat. } a = 2*k1 + 1$ **by** (*meson oddE*)
from *assms* **have** $1 : \exists k2 :: \text{nat. } b = 2*k2 + 1$ **by** (*meson oddE*)
from 0 **have** $4*a \bmod 8 = 4$ **by** *auto*
hence $2:8 \text{ dvd } (4*a - 4)$ **by** (*metis dvd-minus-mod*)

obtain $k2$ **where** $b = 2*k2 + 1$ **using** 1 **by** *auto*
have $2 \text{ dvd } k2*(k2 + 1)$ **by** *auto*
hence $8 \text{ dvd } 4*k2*(k2 + 1)$ **by** (*metis ab-semigroup-mult-class.mult-ac(1) mult-2-right nat-mult-dvd-cancel-disj numeral-Bit0*)
hence $b^2 \bmod 8 = 1$ **using** 1 **by** (*metis One-nat-def Suc-0-mod-numeral(2) assms(4) square-mod-8-eq-1-iff unique-euclidean-semiring-class.cong-def*)
hence $8 \text{ dvd } (b^2 - 1)$ **by** (*metis dvd-minus-mod*)
from 2 **this** **have** $8 \text{ dvd } ((4*a - 4) - (b^2 - 1))$ **using** *dvd-diff-nat* **by** *blast*
from *assms* $0\ 1$ **and** **this** **have** $7:8 \text{ dvd } ((4*a - b^2) - 3)$ **by** *auto*
from *assms* $0\ 1$ **have** $5:4*a - b^2 \neq 1$ **using** *not-one* **by** *auto*
from *assms* $0\ 1$ **have** $6:4*a - b^2 \neq 2$ **using** *not-two* **by** *auto*
from $3\ 5\ 6$ **have** $4*a - b^2 \geq 3$ **by** *auto*
from **this** 7 **have** $8:(4*a - b^2) \bmod 8 = 3$ **using** *mod-nat-eqI* **by** *presburger*

obtain $j\ k\ l$ **where** $\text{ints: odd } j \wedge \text{ odd } k \wedge \text{ odd } l \wedge (4*a - b^2) = j^2 + k^2 + l^2$
using 8 *odd-three-squares-using-mod-eight* **by** *presburger*
define x **where** $x = \text{sort}[j, k, l] ! 2$
define y **where** $y = \text{sort}[j, k, l] ! 1$
define z **where** $z = \text{sort}[j, k, l] ! 0$

have $x^2 + y^2 + z^2 = \text{sum-list } (\text{map } (\lambda x. x^2) [j, k, l])$ **using** *x-def y-def z-def*

by auto
from this ints have a-and-b: $(4*a - b^2) = x^2 + y^2 + z^2$ by auto

have size: $x \geq y \wedge y \geq z$ using x-def y-def z-def by auto
have x-par: $x = j \vee x = k \vee x = l$ using x-def by auto
have y-par: $y = j \vee y = k \vee y = l$ using y-def by auto
have z-par: $z = j \vee z = k \vee z = l$ using z-def by auto
hence parity: $odd\ x \wedge odd\ y \wedge odd\ z$ using ints x-par y-par z-par by fastforce
from 1 have b-par: $odd\ b$ by auto

obtain w::int where w-def: $(w = z \vee w = -z) \wedge (b + x + y + w) \bmod 4 = 0$
using suit-z size parity b-par by presburger

from parity have fac1: $(int\ z) \bmod 4 = 3 \vee (int\ z) \bmod 4 = 1$ by presburger
from parity have fac2: $-z \bmod 4 = 3 \vee -z \bmod 4 = 1$ by presburger
from w-def have fac3: $w \bmod 4 = 3 \vee w \bmod 4 = 1$ using fac1 fac2 by auto

have s-int:4 dvd $(b + x + y + w)$ using b-par parity fac3 w-def by presburger
have b-x-int:2 dvd $(b + x)$ using b-par parity by presburger
have b-y-int:2 dvd $(b + y)$ using b-par parity by presburger
have b-w-int:2 dvd $(b + w)$ using b-par fac3 by presburger

obtain s::int where s-def: $s = (b + x + y + w) \div 4$ using s-int by fastforce
obtain t::int where t-def: $t = (b + x) \div 2 - s$ using s-int b-x-int by blast
obtain u::int where u-def: $u = (b + y) \div 2 - s$ using s-int b-y-int by blast
obtain v::int where v-def: $v = (b + w) \div 2 - s$ using s-int b-w-int by blast

from t-def s-def have t-simp1: $t = (2*b + 2*x) \div 4 - (b + x + y + w) \div 4$ by auto
have t-simp2: $(2*b + 2*x) - (b + x + y + w) = b + x - y - w$ using size by auto
hence t-expre: $t = (b + x - y - w) \div 4$ using t-simp1 by (smt (verit, ccfv-SIG) add-num-simps(1) div-plus-div-distrib-dvd-right numeral-Bit0 of-nat-numeral one-plus-numeral s-int linordered-euclidean-semiring-class.of-nat-div)
from b-x-int have 4 dvd $(2*b + 2*x)$
by (metis distrib-left-numeral mult-2-right nat-mult-dvd-cancel-disj numeral-Bit0)
hence four-div-tn:4 dvd $(b + x - y - w)$ using s-int t-simp2 by presburger

have $(b + x) \div 2 + (b + y) \div 2 = (2*b + x + y) \div 2$
by (smt (verit, best) Groups.add-ac(2) b-y-int div-plus-div-distrib-dvd-right left-add-twice nat-arith.add2)
hence threesum: $t + u + s = (2*b + x + y) \div 2 - s$ using t-def u-def by auto

have 2 dvd $(x + y)$ using parity by auto
hence $(2*b + x + y) \div 2 + (b + w) \div 2 = (2*b + b + x + y + w) \div 2$
by (smt (verit, ccfv-threshold) Num.of-nat-simps(4) b-w-int div-plus-div-distrib-dvd-right landau-product-preprocess(4) numerals(1) of-nat-1 one-plus-numeral linordered-euclidean-semiring-class.of-nat-div)

hence $t+u+s+v = (2*b+b+x+y+w) \text{ div } 2 - s - s$ **using** *v-def threesum by auto*
hence $\text{foursum0}:t+u+s+v = (2*b+b+x+y+w) \text{ div } 2 - (b+x+y+w) \text{ div } 4 -$
 $(b+x+y+w) \text{ div } 4$
using *s-def by auto*
have $\text{foursum1}:(b+x+y+w) \text{ div } 4 + (b+x+y+w) \text{ div } 4 = (b+x+y+w) \text{ div } 2$
using *div-mult-swap s-int by auto*
have $(2*b+b+x+y+w) \text{ div } 2 - (b+x+y+w) \text{ div } 2 = (2*b) \text{ div } 2$ **by auto**
hence $t+u+s+v = (2*b) \text{ div } 2$ **using** *foursum0 foursum1 by linarith*
hence $\text{second}:t+u+s+v = b$ **by auto**

from *a-and-b* **have** $4*a = x^2+y^2+z^2+b^2$
by (*metis Nat.add-diff-assoc2 add-diff-cancel-right' assms(5) less-or-eq-imp-le*)
hence $a = (x^2+y^2+z^2+b^2) \text{ div } 4$ **using** *parity b-par by auto*

from *second* **have** $b\text{-expression}:b^2 = t^2+u^2+s^2+v^2+2*t*u+2*s*v +$
 $2*t*s + 2*t*v + 2*u*s + 2*u*v$ **using** *four-terms-bin-exp-allsum*
by (*metis is-num-normalize(1) nat-arith.add2 of-nat-power*)

define *sn* **where** $\text{sn-def}:sn = b+x+y+w$
from *sn-def s-def* **have** $\text{sn-nums}: 4*s = sn$ **by** (*metis dvd-div-mult-self mult commute*
s-int)

from *sn-def* **have** $\text{sn-sqr}:sn^2 = b^2+x^2+y^2+w^2+2*b*x+2*b*y+2*b*w+2*x*y+2*x*w+2*y*w$

using *four-terms-bin-exp-allsum w-def by auto*
hence $s\text{-pen}:16*s^2 = b^2+x^2+y^2+w^2+2*b*x+2*b*y+2*b*w+2*x*y+2*x*w+2*y*w$
using *sn-nums by auto*
have $4 \text{ dvd } sn$ **using** *s-int sn-def by auto*
hence $16 \text{ dvd } sn^2$ **by auto**
hence $s\text{-sqr-expression}:s^2=(b^2+x^2+y^2+w^2+2*b*x+2*b*y+2*b*w+2*x*y+2*x*w+2*y*w)$
div 16
using *sn-sqr s-pen by auto*

define *tn* **where** $\text{tn-def}:tn = b+x-y-w$
from *tn-def t-expre size four-div-tn* **have** $\text{tn-nums}: 4*t = tn$
by (*metis dvd-div-mult-self mult commute*)
from *size assms* **have** $b+x-y > 0$ **by auto**
hence $tn = \text{int } b + \text{int } x - \text{int } y - w$ **using** *tn-def by auto*
from *this* **have** $\text{tn-sqr}:tn^2 = b^2+x^2+y^2+w^2+2*b*x-2*b*y-2*b*w-2*x*y-2*x*w+2*y*w$
using *four-terms-bin-exp-twodiff w-def by auto*
hence $t\text{-pen}:16*t^2 = b^2+x^2+y^2+w^2+2*b*x-2*b*y-2*b*w-2*x*y-2*x*w+2*y*w$
using *tn-nums by auto*
have $16 \text{ dvd } tn^2$ **using** *tn-def four-div-tn by auto*
hence $t\text{-sqr-expression}:t^2=(b^2+x^2+y^2+w^2+2*b*x-2*b*y-2*b*w-2*x*y-2*x*w+2*y*w)$
div 16
using *tn-sqr t-pen by auto*

from *size s-def t-expre w-def* **have** $\text{sgeqt}:s \geq t$ **by auto**
from *size s-def t-def u-def* **have** $\text{tgequ}:t \geq u$ **by auto**
from *size s-def u-def v-def w-def* **have** $\text{ugeqv}:u \geq v$ **by auto**

from *assms*(6) **have** $12*a < 4*b^2 + 8*b + 16$ **by** *auto*
hence $12*a - 3*b^2 < b^2 + 8*b + 16$ **by** *auto*
hence $12*a - 3*b^2 < (b+4)^2$
by (*smt* (*z3*) *add.commute add.left-commute mult-2 numeral-Bit0 power2-eq-square power2-sum*)
hence *mid-ineq*: $\text{sqrt}(12*a - 3*b^2) < b+4$
by (*meson of-nat-0-le-iff of-nat-power-less-of-nat-cancel-iff real-less-lsqrt*)

define *ab*:*nat* **where** *ab-def*: $ab = 4*a - b^2$
from *assms ab-def* **have** *nonneg-ab*: $ab > 0$ **by** *auto*
from *a-and-b ab-def* **have** *sum-of-sqrs*: $x^2 + y^2 + z^2 = ab$ **by** *auto*
from *this nonneg-ab* **have** $x^2 + y^2 + z^2 > 0$ **by** *auto*
from *this sum-of-sqrs three-terms-Cauchy-Schwarz-nat-ver* **have** $x+y+z \leq \text{sqrt}(3*ab)$
by *auto*
hence *left-ineq*: $x+y+z \leq \text{sqrt}(3*(4*a - b^2))$ **using** *ab-def* **by** *auto*
have $\text{sqrt}(3*(4*a - b^2)) = \text{sqrt}(12*a - 3*b^2)$ **by** (*simp add: diff-mult-distrib2*)
from *left-ineq mid-ineq this* **have** $x+y+z < b+4$ **by** *auto*
hence *num-bound*: $\text{int } b - x - y - z > -4$ **by** *auto*

define *vn* **where** *vn-def*: $vn = \text{int } b + w - x - y$
from *num-bound vn-def w-def* **have** *vn-bound*: $vn > -4$ **by** *auto*
from *w-def* **have** *four-div-sn*: $4 \text{ dvd } (\text{int } b + x + y + w)$ **by** *auto*
from *parity* **have** $4 \text{ dvd } (\text{int } 2*x + 2*y)$
by (*metis Num.of-nat-simps*(5) *even (x + y) distrib-left int-dvd-int-iff nat-mult-dvd-cancel-disj num-double numeral-mult of-nat-add of-nat-numeral*)
hence $4 \text{ dvd } (\text{int } b + x + y + w - 2*x - 2*y)$ **using** *four-div-sn*
by (*smt* (*verit*) *Num.of-nat-simps*(5) *dvd-add-left-iff*)
hence $4 \text{ dvd } vn$ **using** *vn-def* **by** *presburger*

from *v-def s-def* **have** $v = (\text{int } 2*b + 2*w) \text{ div } 4 - (\text{int } b + x + y + w) \text{ div } 4$
by *auto*
hence *v-expre*: $v = (\text{int } b - x - y + w) \text{ div } 4$ **using** *four-div-sn* **by** *fastforce*
hence $v = vn \text{ div } 4$ **using** *vn-def* **by** *auto*
hence $v \geq 0$ **using** *vn-bound four-div-sn* **using** $\langle 4 \text{ dvd } vn \rangle$ **by** *fastforce*
hence *stuv-nonneg*: $s \geq 0 \wedge t \geq 0 \wedge u \geq 0 \wedge v \geq 0$ **using** *sqgt tgequ ugeqv*
by *linarith*

from *vn-def* **have** *vn-sqr*: $vn^2 = b^2 + x^2 + y^2 + w^2 - 2*b*x - 2*b*y + 2*b*w + 2*x*y - 2*x*w - 2*y*w$
using *four-terms-bin-exp-twodiff w-def* **by** *auto*
from $\langle v = vn \text{ div } 4 \rangle$ **have** *vn-is-num*: $v^2 = vn^2 \text{ div } 16$ **using** $\langle 4 \text{ dvd } vn \rangle$ **by** *fastforce*
hence $16 \text{ dvd } vn^2$ **using** *v-def* **using** $\langle 4 \text{ dvd } vn \rangle$ **by** *fastforce*
from *vn-is-num vn-sqr* **have**
v-sqr-expression: $v^2 = (b^2 + x^2 + y^2 + w^2 - 2*b*x - 2*b*y + 2*b*w + 2*x*y - 2*x*w - 2*y*w) \text{ div } 16$ **by** *auto*

define *un* **where** *un-def*: $un = \text{int } b + y - x - w$

from *parity w-def* **have** *even (x+w)* **by** *auto*
from *this parity* **have** $4 \text{ dvd } (\text{int } 2*x+2*w)$
by (*metis distrib-left even-numeral mult-2-right mult-dvd-mono numeral-Bit0 of-nat-numeral*)
hence $4 \text{ dvd } (\text{int } b + x + y + w - 2*x - 2*w)$ **using** *four-div-sn*
by (*smt (verit) Num.of-nat-simps(5) dvd-add-left-iff*)
hence 4 dvd un **using** *un-def* **by** *presburger*

from *u-def s-def* **have** $u = (\text{int } 2*b+2*y) \text{ div } 4 - (\text{int } b + x + y + w) \text{ div } 4$
by *auto*
hence *u-expre:u = (int b-x+y-w) div 4* **using** *four-div-sn* **by** *fastforce*
hence $u = \text{un div } 4$ **using** *un-def* **by** *auto*
from *un-def* **have** *un-sqr:un² = b²+x²+y²+w²+2*b*y-2*b*x-2*b*w-2*y*x-2*y*w+2*x*w*
using *four-terms-bin-exp-twodiff w-def* **by** *auto*
from $\langle u = \text{un div } 4 \rangle$ **have** *un-is-num:u² = un² div 16* **using** $\langle 4 \text{ dvd un} \rangle$ **by**
fastforce
hence 16 dvd un^2 **using** *u-def* **using** $\langle 4 \text{ dvd un} \rangle$ **by** *fastforce*
from *un-is-num un-sqr* **have**
*u-sqr-expression:u² = (b²+x²+y²+w²+2*b*y-2*b*x-2*b*w-2*y*x-2*y*w+2*x*w)*
 $\text{div } 16$ **by** *auto*

from *u-sqr-expression v-sqr-expression* **have**
*uv-simp1:u²+v² = (int b²+x²+y²+w²-2*b*x-2*b*y+2*b*w+2*x*y-2*x*w-2*y*w)*
 $\text{div } 16 +$
 $(\text{int } b^2+x^2+y^2+w^2+2*b*y-2*b*x-2*b*w-2*y*x-2*y*w+2*x*w) \text{ div}$
 16 **by** *auto*
have *uv-simp2:(int b²+x²+y²+w²-2*b*x-2*b*y+2*b*w+2*x*y-2*x*w-2*y*w)+*
 $(\text{int } b^2+x^2+y^2+w^2+2*b*y-2*b*x-2*b*w-2*y*x-2*y*w+2*x*w)=$
 $(\text{int } 2*b^2+2*x^2+2*y^2+2*w^2-4*b*x-4*y*w)$ **by** *auto*
hence $16 \text{ dvd } (\text{int } 2*b^2+2*x^2+2*y^2+2*w^2-4*b*x-4*y*w)$ **by** (*smt (verit)*
 $\langle 16 \text{ dvd un}^2 \rangle \langle 16 \text{ dvd vn}^2 \rangle$
dvd-add-right-iff of-nat-power un-sqr vn-sqr zadd-int-left)
hence *usqr-plus-vsqr:u²+v² = (int 2*b²+2*x²+2*y²+2*w²-4*b*x-4*y*w)*
 $\text{div } 16$
using *uv-simp1 uv-simp2* **by** (*smt (verit, ccfv-threshold) Num.of-nat-simps(4)*
Num.of-nat-simps(5)
 $\langle 16 \text{ dvd vn}^2 \rangle \text{ div-plus-div-distrib-dvd-right power2-eq-square vn-sqr}$)

have *allsum0:s²+t²+u²+v² = (sn²+tn²+un²+vn²) div 16* **using**
 $\langle 16 \text{ dvd vn}^2 \rangle \langle 16 \text{ dvd sn}^2 \rangle$
 $\langle 16 \text{ dvd un}^2 \rangle \langle 16 \text{ dvd tn}^2 \rangle$ *s-sqr-expression t-sqr-expression u-sqr-expression v-sqr-expression*
sn-sqr tn-sqr un-sqr vn-sqr **by** (*metis add commute div-plus-div-distrib-dvd-left*)
have *allsum1:(sn²+tn²+un²+vn²) = (int 4*b²+4*x²+4*y²+4*w²)*

using *sn-sqr tn-sqr un-sqr vn-sqr* **by** *auto*
have $16 \text{ dvd } (\text{sn}^2+\text{tn}^2+\text{un}^2+\text{vn}^2)$
by (*simp add: \langle 16 dvd sn² \rangle \langle 16 dvd tn² \rangle \langle 16 dvd un² \rangle \langle 16 dvd vn² \rangle*)
hence $16 \text{ dvd } 4*(\text{int } b^2+x^2+y^2+w^2)$ **using** *allsum1* **by** *auto*
hence $4 \text{ dvd } (\text{int } b^2+x^2+y^2+w^2)$ **by** *presburger*

```

from allsum1 have  $s^2+t^2+u^2+v^2 = (int\ 4*b^2+4*x^2+4*y^2+4*w^2)$ 

using allsum0 by presburger
hence  $s^2+t^2+u^2+v^2 = 4*(int\ b^2+x^2+y^2+w^2)$  div 16 by simp
hence allsum2: $s^2+t^2+u^2+v^2 = (int\ b^2+x^2+y^2+w^2)$  div 4 by simp

from a-and-b have  $4*a = int\ b^2+x^2+y^2+w^2$  using w-def
  using  $\langle 4 * a = x^2 + y^2 + z^2 + b^2 \rangle$  by fastforce
hence first:a =  $s^2+t^2+u^2+v^2$  using allsum2 by linarith

show ?thesis using first second stuv-nonneg by (smt (verit, best))
qed
end


```

2 Polygonal Number Theorem

2.1 Gauss's Theorem on Triangular Numbers

We show Gauss's theorem which states that every non-negative integer is the sum of three triangles, using the Three Squares Theorem AFP entry [1]. This corresponds to Theorem 1.8 in [2].

```

theory Polygonal-Number-Theorem-Gauss
  imports Polygonal-Number-Theorem-Lemmas
begin

```

The following is the formula for the k -th polygonal number of order $m + 2$.

```

definition polygonal-number :: nat  $\Rightarrow$  nat  $\Rightarrow$  nat
  where polygonal-number  $m\ k = m*k*(k-1)$  div  $2 + k$ 

```

When $m = 1$, the polygonal numbers have order 3 and the formula represents triangular numbers. Gauss showed that all natural numbers can be written as the sum of three triangular numbers. In other words, the triangular numbers form an additive basis of order 3 of the natural numbers.

```

theorem Gauss-Sum-of-Three-Triangles:

```

```

  fixes  $n :: nat$ 
  shows  $\exists\ x\ y\ z. n = polygonal-number\ 1\ x + polygonal-number\ 1\ y + polygonal-number\ 1\ z$ 

```

```

proof -

```

```

  have  $(8 * n + 3) \bmod 8 = 3$  by auto
  then obtain  $a\ b\ c$  where  $0: odd\ a \wedge odd\ b \wedge odd\ c \wedge 8 * n + 3 = a^2 + b^2 + c^2$ 
  using odd-three-squares-using-mod-eight by presburger
  then obtain  $x\ y\ z$  where  $a = 2 * x + 1 \wedge b = 2 * y + 1 \wedge c = 2 * z + 1$  by
(meson oddE)
  hence  $8 * n + 3 = (2 * x + 1)^2 + (2 * y + 1)^2 + (2 * z + 1)^2$ 
  using  $0$  by auto

```

```

hence  $n = (x * x + x + y * y + y + z * z + z) \text{ div } 2$ 
  by (auto simp add: power2-eq-square)
hence  $n\text{-expr}:n = (x * (x + 1) + y * (y + 1) + z * (z + 1)) \text{ div } 2$ 
  by (metis (no-types, lifting) arithmetic-simps(79) nat-arith.add1 nat-distrib(2))

have triangle-identity: polygonal-number 1 k = k*(k+1) div 2 for k
proof –
  have  $k*(k-1)+2*k = k*k+k$  by (simp add: right-diff-distrib')
  hence  $k*(k-1) \text{ div } 2 + k = (k*k+k) \text{ div } 2$ 
    by (metis Groups.add-ac(2) bot-nat-0.not-eq-extremum div-mult-self2 pos2)
  thus ?thesis using polygonal-number-def by simp
qed
from n-expr triangle-identity show ?thesis
  by (metis div-plus-div-distrib-dvd-right even-mult-iff odd-even-add odd-one)
qed
end

```

2.2 Cauchy's Polygonal Number Theorem

We will use the definition of the polygonal numbers from the Gauss Theorem theory file which also imports the Three Squares Theorem AFP entry [1].

```

theory Polygonal-Number-Theorem-Cauchy
  imports Polygonal-Number-Theorem-Gauss
begin

```

The following lemma shows there are two consecutive odd integers in any four consecutive integers.

```

lemma two-consec-odd:
  fixes  $a1\ a2\ a3\ a4 :: \text{int}$ 
  assumes  $a1 - a2 = 1$ 
  assumes  $a2 - a3 = 1$ 
  assumes  $a3 - a4 = 1$ 
  shows  $\exists k1\ k2 :: \text{int}. \{k1, k2\} \subseteq \{a1, a2, a3, a4\} \wedge (k2 = k1 + 2) \wedge \text{odd } k1$ 

```

```

proof –
  have  $c1:\exists k1\ k2 :: \text{int}. \{k1, k2\} \subseteq \{a1, a2, a3, a4\} \wedge (k2 = k1 + 2) \wedge \text{odd } k1$ 
    if odd-case:odd a4
  proof –
    define  $k1$  where  $k1\text{-def}:k1 = a4$ 
    define  $k2$  where  $k2\text{-def}:k2 = k1 + 2$ 
    have  $0:k2 = a2$  using  $k2\text{-def } k1\text{-def}$  assms by simp
    have  $1:\text{odd } k1$  using  $k1\text{-def}$  odd-case by simp
    show  $\exists k1\ k2 :: \text{int}. \{k1, k2\} \subseteq \{a1, a2, a3, a4\} \wedge (k2 = k1 + 2) \wedge \text{odd } k1$ 
      using  $0\ 1\ k1\text{-def } k2\text{-def}$  by auto
  qed

  have  $c2:\exists k1\ k2 :: \text{int}. \{k1, k2\} \subseteq \{a1, a2, a3, a4\} \wedge (k2 = k1 + 2) \wedge \text{odd } k1$ 
    if even-case:even a4

```

```

proof –
  define k1 where k1-def:k1 = a3
  define k2 where k2-def:k2 = k1 + 2
  have 2:odd k1 using even-case assms k1-def by presburger
  have 3:k2 = a1 using k1-def k2-def assms by simp
  show  $\exists k1\ k2 :: int. \{k1, k2\} \subseteq \{a1, a2, a3, a4\} \wedge (k2 = k1+2) \wedge odd\ k1$ 
    using 2 3 k1-def k2-def by auto
  qed
  show ?thesis using c1 c2 by auto
qed

```

This lemma proves that for two consecutive integers b_1 and b_2 , and $r \in \{0, 1, \dots, m-3\}$, numbers of the form $b_1 + r$ and $b_2 + r$ can cover all the congruence classes modulo m .

lemma *cong-classes*:

```

fixes b1 b2 :: int
fixes m :: nat
assumes  $m \geq 4$ 
assumes odd b1
assumes  $b2 = b1 + 2$ 
shows  $\forall N::nat. \exists b::int. \exists r::nat. (r \leq m-3) \wedge [N=b+r] \pmod m \wedge (b = b1 \vee b = b2)$ 

```

proof –

```

have first: $\forall N::nat. \exists b::int. \exists r::nat. (r \leq m-3) \wedge [N=b+r] \pmod m \wedge (b = b1 \vee b = b2)$ 

```

```

  if first-assum:b1 mod m  $\geq 3$ 

```

proof –

```

  define k1 where k1-def:k1 = b1 mod m
  define l where l-def:l =  $m - k1$ 
  have k1-size: $k1 \geq 3$  using first-assum k1-def by simp
  have l-size: $l \leq m-3$  using first-assum k1-def l-def by auto
  have  $(l+k1) \pmod m = 0$  using l-def by auto
  hence  $(l+b1) \pmod m = 0$  using k1-def l-def by (metis mod-add-right-eq)
  define w where w-def:w =  $m-3-l$ 
  have w-size: $w \geq 0 \wedge w \leq m-3$  using w-def l-size l-def k1-def first-assum
    by (smt (verit, best) Euclidean-Rings.pos-mod-bound assms(1) le-antisym
numeral-neq-zero
of-nat-0-less-iff order-trans-rules(22) verit-comp-simplify(3) zero-le-numeral)
  have  $k1 = w+3$  using w-def k1-def l-def w-size first-assum by linarith
  hence  $w+2 = k1-1$  by auto
  hence  $w+2 = (b1-1) \pmod m$  using first-assum k1-def
    by (smt (verit, del-insts) Euclidean-Rings.pos-mod-bound assms(1)
mod-diff-eq mod-pos-pos-trivial of-nat-le-0-iff verit-comp-simplify(8))
  hence w-cover: $w+2 = k1-1$  using k1-def using  $\langle w + 2 = k1 - 1 \rangle$  by
fastforce

```

```

  have  $\exists r::nat. (r \leq m-3) \wedge [N=b1+r] \pmod m$  if asm1: $N \pmod m \geq k1 \wedge N \pmod m \leq m-1$  for N

```

proof –
have $m - (N \bmod m) \leq l$ **using** *asm1 l-def k1-def* **by** *linarith*
hence $\exists d::\text{nat}. d \leq l \wedge [N = k1 + d] \pmod m$ **using** *asm1 k1-def l-def*
by (*metis add commute add-le-cancel-left cong-mod-left cong-refl diff-add-cancel*
diff-le-self le-trans of-nat-mod of-nat-mono zle-iff-zadd)
hence $\exists d::\text{nat}. d \leq l \wedge [N = b1 + d] \pmod m$ **using** *k1-def*
by (*metis mod-add-left-eq unique-euclidean-semiring-class.cong-def*)
thus $\exists r::\text{nat}. (r \leq m-3) \wedge [N = b1 + r] \pmod m$ **using** *l-size*
by (*smt (verit, best) nat-leq-as-int*)
qed
hence $c1: \exists b::\text{int}. \exists r::\text{nat}. (r \leq m-3) \wedge [N = b+r] \pmod m \wedge (b = b1 \vee b =$
 $b2)$ **if** *asm1: $N \bmod m \geq k1 \wedge N \bmod m \leq m-1$* **for** N **using** *asm1* **by** *blast*

have $c2: \exists r::\text{nat}. (r \leq m-3) \wedge [N = b1 + r] \pmod m$ **if** *asm2: $N \bmod m = 0$* **for**
 N **using** *l-def k1-def*
by (*smt (verit, ccfv-threshold) $\langle l + b1 \rangle \bmod \text{int } m = 0$*) *add-diff-cancel-left'*
cong-0-iff
cong-sym cong-trans diff-add-cancel diff-ge-0-iff-ge dvd-eq-mod-eq-0 int-dvd-int-iff
nat-0-le
of-nat-le-iff that w-def w-size
hence $c2: \exists b::\text{int}. \exists r::\text{nat}. (r \leq m-3) \wedge [N = b+r] \pmod m \wedge (b = b1 \vee b =$
 $b2)$
if *asm2: $N \bmod m = 0$* **for** N **using** *asm2* **by** *metis*

have $\exists r::\text{nat}. (r \leq m-3) \wedge [N = b1 + r] \pmod m$ **if** *asm3: $N \bmod m > 0 \wedge N$*
 $\bmod m \leq w$ **for** N

proof –
have $l + (N \bmod m) \leq m-3$ **using** *asm3 w-def* **by** *auto*
hence $\exists d::\text{nat}. (d \leq w) \wedge [N = k1 + l + d] \pmod m$ **using** *asm3 w-def k1-def*
l-def
by (*smt (verit, ccfv-threshold) minus-mod-self2 mod-mod-trivial of-nat-mod*
unique-euclidean-semiring-class.cong-def)
hence $\exists d::\text{nat}. (d \leq w) \wedge [N = b1 + l + d] \pmod m$ **using** *k1-def* **by** (*metis*
(mono-tags,
opaque-lifting) mod-add-left-eq unique-euclidean-semiring-class.cong-def)
hence $\exists r::\text{nat}. (r \leq w+l) \wedge [N = b1 + r] \pmod m$ **by** (*smt (verit) add commute*
add.left-commute le-add-same-cancel2 of-nat-0-le-iff w-def w-size zero-le-imp-eq-int)
thus $\exists r::\text{nat}. (r \leq m-3) \wedge [N = b1 + r] \pmod m$ **using** *w-def* **by** *auto*
qed
hence $\exists b::\text{int}. \exists r::\text{nat}. (r \leq m-3) \wedge [N = b+r] \pmod m \wedge (b = b1 \vee b = b2)$
if *asm3: $N \bmod m > 0 \wedge N \bmod m \leq w$* **for** N **using** *asm3* **by** *blast*
hence $c3: \exists b::\text{int}. \exists r::\text{nat}. (r \leq m-3) \wedge [N = b+r] \pmod m \wedge (b = b1 \vee b =$
 $b2)$
if *asm8: $N \bmod m > 0 \wedge N \bmod m \leq k1-3$* **using** *asm8 w-cover* **by** *auto*

have $\exists r::\text{nat}. (r \leq m-3) \wedge [N = b2 + r] \pmod m$ **if** *asm4: $N \bmod m = w+1 \vee N$*
 $\bmod m = w+2$ **for** N

proof –
have $c4-1: [N = b2 + (m-3)] \pmod m$ **if** *asm5: $N \bmod m = w+2$* **for** N **using**

asm5 w-def assms(3) l-def
by (*smt (verit) $\langle w + 2 = (b1 - 1) \text{ mod int } m \rangle \langle w + 2 = k1 - 1 \rangle$*)
mod-add-self1 of-nat-mod
unique-euclidean-semiring-class.cong-def
hence [$N-1 = b2+(m-4)$] (*mod m*) **if** *asm5:N mod m = w+2* **for** *N*
by (*smt (verit, ccfv-threshold) Num.of-nat-simps(2) $\langle w + 2 = k1 - 1 \rangle$*)
asm5 assms(1)
cong-iff-lin first-assum k1-def l-def mod-less-eq-dividend numeral-Bit0 of-nat-diff
of-nat-le-iff
of-nat-numeral semiring-norm(172) w-def
hence [$N = b2+(m-4)$] (*mod m*) **if** *asm6:N mod m = w+1* **for** *N* **using**
asm6
by (*metis $\langle w + 2 = (b1 - 1) \text{ mod int } m \rangle$ add-diff-cancel-right' arith-special(3)*)
int-ops(4)
is-num-normalize(1) mod-add-left-eq mod-diff-left-eq of-nat-mod
thus ?thesis **using** *c4-1* **by** (*metis asm4 diff-le-mono2 nat-le-linear nu-*
meral-le-iff
verit-comp-simplify(10) verit-comp-simplify(13))
qed
hence $\exists b::int. \exists r::nat. (r \leq m-3) \wedge [N=b+r] \text{ (mod } m) \wedge (b = b1 \vee b = b2)$
if *asm4:N mod m = w+1* \vee *N mod m = w+2* **for** *N* **using** *asm4* **by** *blast*
hence $c4:\exists b::int. \exists r::nat. (r \leq m-3) \wedge [N=b+r] \text{ (mod } m) \wedge (b = b1 \vee b =$
 $b2)$
if *asm7:N mod m = k1-2* \vee *N mod m = k1-1* **for** *N* **using** *w-cover asm7*
by *auto*

have $\exists b::int. \exists r::nat. (r \leq m-3) \wedge [N=b+r] \text{ (mod } m) \wedge (b = b1 \vee b = b2)$
if *asm10:N mod m ≥ 0 \wedge N mod m $\leq w$* **for** *N* **using** *c2 c3 asm10*
using $\langle \wedge N. 0 < N \text{ mod } m \wedge \text{int } (N \text{ mod } m) \leq w \implies \exists b r. r \leq m - 3 \wedge$
 $[\text{int } N = b + \text{int } r]$
 $(\text{mod int } m) \wedge (b = b1 \vee b = b2) \rangle$ **by** *blast*
hence $c5:\exists b::int. \exists r::nat. (r \leq m-3) \wedge [N=b+r] \text{ (mod } m) \wedge (b = b1 \vee b =$
 $b2)$
if *asm11:N mod m ≥ 0 \wedge N mod m $\leq k1-3$* **for** *N* **using** *w-cover* **using**
asm11 **by** *force*

have $c6:\exists b::int. \exists r::nat. (r \leq m-3) \wedge [N=b+r] \text{ (mod } m) \wedge (b = b1 \vee b =$
 $b2)$
if *asm9:(N mod m ≥ 0 \wedge N mod m $\leq k1-3) \vee$ N mod m = $k1-2$ \vee N mod
 $m = k1-1$ **for** *N*
using *c5 c4 asm9* **by** *blast*

hence $c7:\exists b::int. \exists r::nat. (r \leq m-3) \wedge [N=b+r] \text{ (mod } m) \wedge (b = b1 \vee b =$
 $b2)$
if *asm12:(N mod m ≥ 0 \wedge N mod m $\leq k1-3) \vee$ N mod m = $k1-2$ \vee N mod
 $m = k1-1$ \vee
 $(N \text{ mod } m \geq k1 \wedge N \text{ mod } m \leq m-1)$ **for** *N* **using** *asm12 c1* **by** *blast*

have $\forall N::nat. (N \text{ mod } m \geq 0 \wedge N \text{ mod } m \leq k1-3) \vee N \text{ mod } m = k1-2 \vee N$**


```

mod m = k1-1 ∨
(N mod m ≥ k1 ∧ N mod m ≤ m-1) using k1-def
  by (smt (verit, best) Suc-pred' assms(1) bot-nat-0.extremum le-simps(2)
mod-less-divisor
not-numeral-le-zero of-nat-0-less-iff of-nat-le-0-iff)

  thus ?thesis using c7 by auto
qed

  have second:∀ N::nat. ∃ b::int. ∃ r::nat. (r ≤ m-3) ∧ [N=b+r] (mod m) ∧ (b =
b1 ∨ b = b2)
  if second-assum:b1 mod m ≥ 0 ∧ b1 mod m ≤ 2
  proof -
  have case1:∀ N::nat. ∃ b::int. ∃ r::nat. (r ≤ m-3) ∧ [N=b+r] (mod m) ∧ (b
= b1 ∨ b = b2)
  if case1-assum:b1 mod m = 0
  proof -
  have ∃ r::nat. (r ≤ m-3) ∧ [N = b1+r] (mod m) if case1-1-assum:N mod
m ≤ m-3 for N
  using case1-assum case1-1-assum
  by (metis cong-add-rcancel-0 cong-mod-left cong-refl cong-sym-eq zmod-int)
  hence case1-1:∃ b::int. ∃ r::nat. (r ≤ m-3) ∧ [N=b+r] (mod m) ∧ (b = b1
∨ b = b2)
  if case1-1-assum:N mod m ≤ m-3 for N using case1-1-assum by blast

  have [N = b1+(m-2)] (mod m) if case1-2-assum:N mod m = m-2 for N
using case1-2-assum
case1-assum by (metis (no-types, opaque-lifting) add commute cong-add-lcancel-0
cong-mod-right of-nat-mod unique-euclidean-semiring-class.cong-def)
  hence [N = b2+(m-4)] (mod m) if case1-2-assum:N mod m = m-2 for N
using case1-2-assum assms(3)
  by (smt (verit, best) add-leD2 assms(1) int-ops(2) numeral-Bit0 of-nat-diff
of-nat-numeral
semiring-norm(172))
  hence ∃ r::nat. (r ≤ m-3) ∧ [N = b2+r] (mod m) if case1-2-assum:N mod
m = m-2 for N
  using case1-2-assum
  by (meson diff-le-mono2 less-num-simps(2) numeral-le-iff verit-comp-simplify(15))
  hence case1-2:∃ b::int. ∃ r::nat. (r ≤ m-3) ∧ [N=b+r] (mod m) ∧ (b = b1
∨ b = b2)
  if case1-2-assum:N mod m = m-2 for N using case1-2-assum by blast

  have [N = b1+(m-1)] (mod m) if case1-3-assum:N mod m = m-1 for N
using case1-3-assum
case1-assum by (metis (no-types, opaque-lifting) add commute cong-add-lcancel-0
cong-mod-right of-nat-mod unique-euclidean-semiring-class.cong-def)
  hence [N = b2+(m-3)] (mod m) if case1-3-assum:N mod m = m-1 for N
using case1-3-assum assms(3)
  by (smt (verit, best) assms(1) int-ops(2) int-ops(6) numeral-Bit0 nu

```

meral-Bit1 of-nat-mono
of-nat-numeral semiring-norm(172))
hence $\exists r::nat. (r \leq m-3) \wedge [N = b2+r] \pmod m$ **if** *case1-3-assum:N mod m = m-1 for N*
using *case1-3-assum by blast*
hence *case1-3:* $\exists b::int. \exists r::nat. (r \leq m-3) \wedge [N=b+r] \pmod m \wedge (b = b1 \vee b = b2)$
if *case1-3-assum:N mod m = m-1 for N using case1-3-assum by blast*

have $\forall N::nat. (N \pmod m = m-1) \vee (N \pmod m = m-2) \vee (N \pmod m \leq m-3)$
by (*smt (verit, ccfv-threshold) Suc-pred' assms(1) bot-nat-0.not-eq-extremum diff-diff-add diff-is-0-eq' le-simps(2) mod-less-divisor nat-1-add-1 nat-less-le not-numeral-le-zero numeral.simps(3) semiring-norm(172))*)
thus *?thesis using case1-1 case1-2 case1-3 by blast*
qed

have *case2:* $\forall N::nat. \exists b::int. \exists r::nat. (r \leq m-3) \wedge [N=b+r] \pmod m \wedge (b = b1 \vee b = b2)$
if *case2-assum:b1 mod m = 1*
proof –
have *case2b2:b2 mod m = 3 using case2-assum assms(3) by (smt (verit) assms(1) int-ops(2) mod-add-eq mod-pos-pos-trivial numeral-Bit0 of-nat-mono of-nat-numeral semiring-norm(172))*

have $\exists r::nat. (r \leq m-3) \wedge [N = b2+r] \pmod m$ **if** *case2-1-assum:N mod m = m-1 for N*
proof –
have $[N = 3+(m-4)] \pmod m$ **using** *case2-1-assum*
by (*metis (mono-tags, lifting) Suc-eq-plus1 Suc-numeral add-diff-cancel-left arithmetic-simps(1) arithmetic-simps(7) assms(1)mod-mod-trivial ordered-cancel-comm-monoid-diff-class.diff-add-assoc unique-euclidean-semiring-class.cong-def*)
hence $[N = b2+(m-4)] \pmod m$ **using** *case2b2*
by (*metis (mono-tags, lifting) Num.of-nat-simps(4) mod-add-left-eq of-nat-mod of-nat-numeral unique-euclidean-semiring-class.cong-def*)
thus *?thesis using le-diff-conv by fastforce*
qed
hence *case2-1:* $\exists b::int. \exists r::nat. (r \leq m-3) \wedge [N=b+r] \pmod m \wedge (b = b1 \vee b = b2)$
if *case2-1-assum:N mod m = m-1 for N using case2-1-assum by blast*

have $\exists r::nat. (r \leq m-3) \wedge [N = b2+r] \pmod m$ **if** *case2-2-assum:N mod m = 0 for N*
proof –
have $(3+(m-3)) \pmod m = 0$ **using** *assms(1) by fastforce*
hence $(b2+(m-3)) \pmod m = 0$ **using** *case2b2 by (metis Num.of-nat-simps(1) Num.of-nat-simps(4) mod-add-left-eq of-nat-mod of-nat-numeral)*

thus *?thesis using case2-2-assum*
by (*metis int-ops(1) nat-le-linear of-nat-mod unique-euclidean-semiring-class.cong-def*)
qed
hence *case2-2:∃ b::int. ∃ r::nat. (r ≤ m-3) ∧ [N=b+r] (mod m) ∧ (b = b1*
 $\vee b = b2)$
if *case2-2-assum:N mod m = 0 for N using case2-2-assum by metis*

have $\exists r::nat. (r \leq m-3) \wedge [N = b1+r] \pmod m$ **if**
case2-3-assum:N mod m ≤ m-2 ∧ N mod m ≥ 1 for N
proof –
have $\exists r::nat. (r \leq m-3) \wedge ((b1+r) \pmod m = l)$ **if** *asml:l ≥ 1 ∧ l ≤ m-2 for l*
proof –
define *r where r-def:r = l-1*
from *asml have r-range:r ≥ 0 ∧ r ≤ m-3 using r-def by linarith*
have $(1+r) \pmod m = l$ **using** *asml r-def r-range by fastforce*
hence $(b1+r) \pmod m = l$ **using** *case2-assum*
by (*metis Num.of-nat-simps(3) int-ops(9) mod-add-left-eq plus-1-eq-Suc*)
thus *?thesis using asml r-range by blast*
qed
thus *?thesis using case2-3-assum*
by (*metis case2-3-assum of-nat-mod unique-euclidean-semiring-class.cong-def*)
qed
hence *case2-3:∃ b::int. ∃ r::nat. (r ≤ m-3) ∧ [N=b+r] (mod m) ∧ (b = b1*
 $\vee b = b2)$
if *case2-3-assum:N mod m ≤ m-2 ∧ N mod m ≥ 1 for N using case2-3-assum*
by *blast*

have $\forall N::nat. N \pmod m = 0 \vee (N \pmod m \geq 1 \wedge N \pmod m \leq m-1)$ **by** (*metis*
One-nat-def Suc-pred
assms(1) bot-nat-0.extremum-uniqueI leI less-Suc-eq-le mod-less-divisor not-numeral-le-zero)
hence $\forall N::nat. N \pmod m = 0 \vee (N \pmod m \geq 1 \wedge N \pmod m \leq m-2) \vee N$
 $\pmod m = m-1$
by (*smt (verit) arithmetic-simps(68) diff-diff-eq le-add-diff-inverse le-neq-implies-less*
le-simps(2)
le-trans plus-1-eq-Suc)
thus *?thesis using case2-1 case2-2 case2-3 by (metis <math>\wedge N. N \pmod m \leq m - 2 \wedge 1 \leq N \pmod m \implies \exists r \leq m - 3. [int N = b1 + int r] \pmod{int m}>*)

have *case3:∃ N::nat. ∃ b::int. ∃ r::nat. (r ≤ m-3) ∧ [N=b+r] (mod m) ∧ (b*
 $= b1 \vee b = b2)$
if *case3-assum:b1 mod m = 2*
proof –
have *case3b2:b2 mod m = 4*
using *assms case3-assum*
by (*smt (verit, ccfv-SIG) Euclidean-Rings.pos-mod-sign dvd-mod-imp-dvd*
even-numeral int-ops(2)
int-ops(4) mod-diff-eq mod-pos-pos-trivial nat-1-add-1 numeral-Bit0)

of-nat-le-iff
of-nat-numeral plus-1-eq-Suc

have $\exists r::\text{nat. } (r \leq m-3) \wedge [N = b2+r] \pmod m$ **if** *case3-1-assum: $N \pmod m = 0 \vee N \pmod m = 1$ for N*

proof –

have $(4+(m-3)) \pmod m = (4+m-3) \pmod m$ **using** *assms(1)* **by** *auto*

have $(4+m-3) \pmod m = (1+m) \pmod m$ **by** *simp*

hence $(4+(m-3)) \pmod m = 1$ **using** $\langle (4+(m-3)) \pmod m = (4+m-3) \pmod m \rangle$

by (*smt (verit, best) Euclidean-Rings.pos-mod-bound add-lessD1 arith-special(2) assms(1) case3b2*
landau-product-preprocess(4) mod-add-self2 mod-less numeral-Bit0 of-nat-numeral order-le-less)

hence *caseone: $(b2+(m-3)) \pmod m = 1$ using case3b2*

by (*metis Num.of-nat-simps(2) Num.of-nat-simps(4) mod-add-left-eq of-nat-mod of-nat-numeral*)

have $(4+(m-4)) \pmod m = 0$ **using** *assms(1)* **by** *auto*

hence *casezero: $(b2+(m-4)) \pmod m = 0$ using case3b2*

by (*metis (full-types) Num.of-nat-simps(1) Num.of-nat-simps(4) mod-add-left-eq of-nat-mod of-nat-numeral*)

show *?thesis using caseone casezero case3-1-assum*

by (*metis cong-int cong-mod-right cong-refl diff-le-mono2 nat-le-linear numeral-le-iff of-nat-0 of-nat-1 semiring-norm(69) semiring-norm(72)*)

qed

hence *case3-1: $\exists b::\text{int. } \exists r::\text{nat. } (r \leq m-3) \wedge [N=b+r] \pmod m \wedge (b = b1 \vee b = b2)$*

if *case3-1-assum: $N \pmod m = 0 \vee N \pmod m = 1$ for N* **using** *case3-1-assum* **by** *metis*

have $\exists r::\text{nat. } (r \leq m-3) \wedge [N = b1+r] \pmod m$ **if** *case3-2-assum: $N \pmod m \geq 2 \wedge N \pmod m \leq m-1$ for N*

proof –

have $\exists r::\text{nat. } (r \leq m-3) \wedge ((b1+r) \pmod m = l)$ **if** *asml1: $l \geq 2 \wedge l \leq m-1$ for l*

proof –

define *r1* **where** *r1-def: $r1 = l-2$*

from *asml1* **have** *r1-range: $r1 \geq 0 \wedge r1 \leq m-2$* **using** *r1-def* **by** *linarith*

have $(2+r1) \pmod m = l$ **using** *asml1 r1-def r1-range* **by** *fastforce*

hence $(b1+r1) \pmod m = l$ **using** *case3-assum*

by (*metis Num.of-nat-simps(4) mod-add-left-eq of-nat-mod of-nat-numeral*)

thus *?thesis using asml1 r1-range* **by** (*metis One-nat-def diff-diff-add diff-le-mono nat-1-add-1 numeral-3-eq-3 plus-1-eq-Suc r1-def*)

qed

thus *?thesis using case3-2-assum*

```

    by (metis case3-2-assum of-nat-mod unique-euclidean-semiring-class.cong-def)
  qed
  hence case3-2:  $\exists b::int. \exists r::nat. (r \leq m-3) \wedge [N=b+r] \pmod m \wedge (b = b1 \vee b = b2)$ 
  if case3-2-assum:  $N \pmod m \geq 2 \wedge N \pmod m \leq m-1$  for  $N$  using case3-2-assum
  by blast

  have  $\forall N::nat. N \pmod m = 0 \vee (N \pmod m \geq 1 \wedge N \pmod m \leq m-1)$  by (metis
  Suc-pred' assms(1)
  bot-nat-0.not-eq-extremum less-one mod-Suc-le-divisor rel-simps(76) verit-comp-simplify1(3))
  hence  $\forall N::nat. N \pmod m = 0 \vee N \pmod m = 1 \vee (N \pmod m \geq 2 \wedge N \pmod m \leq m-1)$ 
  by (metis Suc-eq-plus1 le-neq-implies-less le-simps(3) nat-1-add-1)

  thus ?thesis using case3-1 case3-2 by blast
  qed

  show ?thesis using case1 case2 case3 using that by fastforce
  qed

  show ?thesis using first second using assms(1) by force
  qed

```

The strong form of Cauchy's polygonal number theorem shows for a natural number N satisfying certain conditions, it may be written as the sum of $m + 1$ polygonal numbers of order $m + 2$, at most four of which are different from 0 or 1. This corresponds to Theorem 1.9 in [2].

theorem *Strong-Form-of-Cauchy-Polygonal-Number-Theorem-1:*

```

  fixes  $m N :: nat$ 
  assumes  $m \geq 4$ 
  assumes  $N \geq 108 * m$ 
  shows  $\exists xs :: nat\ list. (length\ xs = m + 1) \wedge (sum\ list\ xs = N) \wedge (\forall k \leq 3. \exists a. xs! k = polygonal\ number\ m\ a) \wedge (\forall k \in \{4..m\}. xs! k = 0 \vee xs! k = 1)$ 

```

proof –

```

  define  $L$  where  $L\text{-def}: L = (2/3 + \sqrt{8 * N / m - 8}) - (1/2 + \sqrt{6 * N / m - 3})$ 
  from assms  $L\text{-def}$  have  $L > 4$  using interval-length-greater-than-four
  apply (rule-tac  $N = of\ nat\ N$  and  $m = of\ nat\ m$  in interval-length-greater-than-four)
  by auto
  define  $c1$  where  $c1\text{-def}: c1 = \lceil 1/2 + \sqrt{6 * N / m - 3} \rceil$ 
  define  $c2$  where  $c2\text{-def}: c2 = c1 + 1$ 
  define  $c3$  where  $c3\text{-def}: c3 = c1 + 2$ 
  define  $c4$  where  $c4\text{-def}: c4 = c1 + 3$ 
  from  $\langle L > 4 \rangle$   $c1\text{-def}$   $c2\text{-def}$   $c3\text{-def}$   $c4\text{-def}$   $L\text{-def}$  have  $c4 < (2/3 + \sqrt{8 * N / m - 8})$  by linarith

  have  $N / m \geq 108$  using assms using le-divide-eq by fastforce

```

hence $\text{sqrt}(6*N/m - 3) \geq 1$ **by** *simp*
hence $1/2 + \text{sqrt}(6*N/m - 3) \geq 1$ **by** *linarith*
hence $c1 \geq 1$ **using** *c1-def* **by** *simp*

obtain $b1\ b2$ **where** $bproperties:\{b1, b2\} \subseteq \{c1, c2, c3, c4\} \wedge (b2 = b1+2) \wedge$
odd b1
using *two-consec-odd c1-def c2-def c3-def c4-def* **by** (*metis (no-types, opaque-lifting)*
Groups.add-ac(2)
empty-subsetI even-plus-one-iff insert-commute insert-mono nat-arith.add1 numeral.simps(2)
numeral.simps(3))
have $b1\text{and}b2:\text{odd } b1 \wedge b2 = b1+2$ **using** *bproperties* **by** *auto*
have $b1pos:b1 \geq 1$ **using** $\langle c1 \geq 1 \rangle$ *c2-def c3-def c4-def bproperties* **by** *auto*
hence $b2pos:b2 \geq 3$ **using** *bproperties* **by** *simp*
have $b2odd:\text{odd } b2$ **using** *bproperties* **by** *simp*

obtain $b\ r$ **where** $b-r:r \leq m-3 \wedge (b = b1 \vee b = b2) \wedge [int\ N = b+r] \pmod{m}$
using *b1andb2 assms(1)*
cong-classes **by** *meson*
have $bpos:b \geq 1$ **using** *b1pos b2pos b-r* **by** *auto*
have $bodd:\text{odd } b$ **using** *b-r bproperties* **by** *auto*

define a **where** $a-def:a = b+2*(N-b-r) \text{ div } m$
have $m-div-num:m \text{ dvd } (N-b-r)$ **using** *b-r*
by (*simp add: diff-diff-add mod-eq-dvd-iff unique-euclidean-semiring-class.cong-def*)
hence $(N-b-r)/m = (N-b-r) \text{ div } m$ **by** (*simp add: real-of-int-div*)
hence $a-def1:a = b+2*(N-b-r)/m$ **using** $a-def$ **by** (*metis <int m dvd int N -*
b - int r>
dvd-add-right-iff mult-2 of-int-add of-int-of-nat-eq real-of-int-div)
have $N-m > 0$ **using** *assms* **by** *linarith*
hence $N-r > 0$ **using** *b-r* **by** *force*
hence $(N-b-r) = (N-r) - b$ **by** *linarith*
hence $(N-b-r)/m = (N-r)/m - b/m$ **by** (*metis diff-divide-distrib int-of-reals(3)*
of-int-of-nat-eq)
hence $a = b+2*((N-r)/m - b/m)$ **using** $a-def1$ **by** (*metis int-of-reals(6)*
of-int-mult times-divide-eq-right)
hence $a-def2:a = b - b*2/m + 2*(N-r)/m$ **by** *simp*
have $b*(1-2/m) = b*1 - b*(2/m)$ **by** (*simp add: Rings.ring-distrib(4)*)
hence $a-def3:a = b*(1-2/m) + 2*(N-r)/m$ **using** $a-def2$ **by** *simp*
have $1-2/m > 0$ **using** *assms(1)* **by** *simp*
hence $size1:b*(1-2/m) > 0$ **using** *bpos* **by** *simp*
have $N-r > 0$ **using** *b-r assms* **by** *auto*
hence $size2:2*(N-r)/m > 0$ **using** *assms(1)* **by** *simp*
have $a\text{pos}:a \geq 1$ **using** *size1 size2 a-def3*
by *linarith*

have $\text{odd } (b+2*(N-b-r) \text{ div } m)$ **using** *m-div-num b-r b2odd bproperties*
by (*metis div-mult-swap zdvd-reduce*)
hence $a\text{odd}:\text{odd } a$ **using** $a-def$ **by** *simp*

from *a-def1* **have** $a-b = 2*(N-b-r)/m$ **by** *simp*
hence $m*(a-b)/2 = N-b-r$ **using** *assms(1)* **by** *simp*
hence $N\text{-expr}: N = r+b+m*(a-b)/2$ **by** *simp*

have $b1 \geq c1$ **using** *bproperties c2-def c3-def c4-def* **by** *force*
hence $b1 \geq 1/2 + \sqrt{6*N/m - 3}$ **using** *c1-def* **using** *ceiling-le-iff* **by** *blast*
have $b\text{-ineq1}: b \geq 1/2 + \sqrt{6*N/m - 3}$ **using** *b-r bproperties*
using $\langle 1 / 2 + \sqrt{\text{real } (6 * N) / \text{real } m - 3} \leq \text{real-of-int } b1 \rangle$ **by** *fastforce*

have $b2 \leq c4$ **using** *bproperties c1-def c2-def c3-def c4-def* **by** *fastforce*
hence $b2 \leq (2/3 + \sqrt{8*N/m - 8})$
using $\langle \text{real-of-int } c4 < 2 / 3 + \sqrt{\text{real } (8 * N) / \text{real } m - 8} \rangle$ **by** *linarith*
hence $b\text{-ineq2}: b \leq (2/3 + \sqrt{8*N/m - 8})$ **using** *b-r bproperties* **by** *linarith*

define *Nr* **where** $Nr = \text{real-of-nat } N$
define *mr* **where** $mr = \text{real } m$
define *ar* **where** $ar = \text{real-of-int } a$
define *br* **where** $br = \text{real-of-int } b$
define *rr* **where** $rr = \text{real-of-nat } r$
from *assms(1)* **have** $mr \geq 3$ **using** *mr-def* **by** *auto*
from *assms(2)* **have** $N \geq 2*m$ **by** *simp*
hence $Nr \geq 2*mr$ **using** *Nr-def mr-def* $\langle N \geq 2 * m \rangle$ **by** *auto*
moreover **have** $br \geq 0$ **using** *br-def bpos* **by** *auto*
moreover **have** $mr \geq 3$ **using** *mr-def assms* **by** *auto*
moreover **have** $ar \geq 0$ **using** *ar-def apos* **by** *auto*
moreover **have** $rr \geq 0$ **using** *rr-def b-r* **by** *auto*
moreover **have** $mr > rr$ **using** *mr-def rr-def b-r assms(1)* **by** *linarith*
moreover **have** $Nr = mr*(ar-br)/2 + br + rr$ **using** *Nr-def mr-def ar-def br-def*
N-expr rr-def **by** *auto*
moreover **have** $1/2 + \sqrt{6*Nr/mr - 3} \leq br \wedge br \leq 2/3 + \sqrt{8*Nr/mr - 8}$ **using**
Nr-def mr-def br-def b-ineq1 b-ineq2 **by** *auto*
ultimately **have** $br^2 < 4*ar \wedge 3*ar < br^2 + 2*br + 4$ **using** *Cauchy-lemma* **by**
auto
hence *real-ineq*: $(\text{real-of-int } b)^2 < 4*(\text{real-of-int } a) \wedge 3*(\text{real-of-int } a) < (\text{real-of-int } b)^2 + 2*(\text{real-of-int } b) + 4$
using *br-def ar-def* **by** *auto*
hence *int-ineq1*: $b^2 < 4*a$ **using** *of-int-less-iff* **by** *fastforce*
from *real-ineq* **have** *int-ineq2*: $3*a < b^2 + 2*b + 4$ **using** *of-int-less-iff* **by** *fastforce*

have *con1*: $\text{nat } a \geq 1$ **using** *apos* **by** *auto*
have *con2*: $\text{nat } b \geq 1$ **using** *bpos* **by** *auto*
have *con3*: *odd* ($\text{nat } a$) **using** *aodd apos even-nat-iff* **by** *auto*
have *con4*: *odd* ($\text{nat } b$) **using** *bodd bpos even-nat-iff* **by** *auto*
have $(\text{nat } b)^2 = b^2$ **using** $\langle \text{nat } b \geq 1 \rangle$ **by** *auto*
hence *con5*: $(\text{nat } b)^2 < 4*(\text{nat } a)$ **using** *int-ineq1* **by** *linarith*
have *con6*: $3*(\text{nat } a) < (\text{nat } b)^2 + 2*(\text{nat } b) + 4$ **using** $\langle (\text{nat } b)^2 = b^2 \rangle$ *int-ineq2*
by *linarith*
obtain $s\ t\ u\ v$ **where** $stuv: s \geq 0 \wedge t \geq 0 \wedge u \geq 0 \wedge v \geq 0 \wedge \text{int}(\text{nat } a) = s^2$

$+ t^2 + u^2 + v^2 \wedge$
 $\text{int}(\text{nat } b) = s+t+u+v$ **using** *four-nonneg-int-sum con1 con2 con3 con4 con5 con6* **by** *presburger*
have *a-expr*: $a = s^2 + t^2 + u^2 + v^2$ **using** *apos stuv* **by** *linarith*
have *b-expr*: $b = s+t+u+v$ **using** *bpos stuv* **by** *linarith*

from *N-expr* **have** $N = m/2*(s^2-s+t^2-t+u^2-u+v^2-v)+r+(s+t+u+v)$
using *a-expr b-expr* **by** *simp*
hence *N-expr2*: $N = m/2*(s^2-s) + m/2*(t^2-t) + m/2*(u^2-u) + m/2*(v^2-v) + r + (s+t+u+v)$
by (*metis (no-types, opaque-lifting) add-diff-eq nat-distrib(2) of-int-add*)
have *s-div2*: $m/2*(s^2-s) = m*(s^2-s) \text{ div } 2$ **using** *real-of-int-div* **by** *auto*
have *t-div2*: $m/2*(t^2-t) = m*(t^2-t) \text{ div } 2$ **using** *real-of-int-div* **by** *auto*
have *u-div2*: $m/2*(u^2-u) = m*(u^2-u) \text{ div } 2$ **using** *real-of-int-div* **by** *auto*
have *v-div2*: $m/2*(v^2-v) = m*(v^2-v) \text{ div } 2$ **using** *real-of-int-div* **by** *auto*
have *N-expr3*: $N = (m*(s^2-s) \text{ div } 2 + s) + (m*(t^2-t) \text{ div } 2 + t) + (m*(u^2-u) \text{ div } 2 + u) + (m*(v^2-v) \text{ div } 2 + v) + r$
using *s-div2 t-div2 u-div2 v-div2 N-expr2* **by** *simp*

define *sn* **where** $sn = \text{nat } s$
define *tn* **where** $tn = \text{nat } t$
define *un* **where** $un = \text{nat } u$
define *vn* **where** $vn = \text{nat } v$
have *seqsn*: $s^2-s = sn^2 - sn$ **using** *stuv sn-def*
by (*metis int-nat-eq le-refl of-nat-diff of-nat-power power2-nat-le-imp-le*)
have *teqtn*: $t^2-t = tn^2 - tn$ **using** *stuv tn-def*
by (*metis int-nat-eq le-refl of-nat-diff of-nat-power power2-nat-le-imp-le*)
have *uequn*: $u^2-u = un^2 - un$ **using** *stuv un-def*
by (*metis int-nat-eq le-refl of-nat-diff of-nat-power power2-nat-le-imp-le*)
have *veqvn*: $v^2-v = vn^2 - vn$ **using** *stuv vn-def*
by (*metis int-nat-eq le-refl of-nat-diff of-nat-power power2-nat-le-imp-le*)

from *N-expr3* **have**
 $N = (m*(sn^2-sn) \text{ div } 2 + s) + (m*(tn^2-tn) \text{ div } 2 + t) + (m*(un^2-un) \text{ div } 2 + u) + (m*(vn^2-vn) \text{ div } 2 + v) + r$
using *seqsn teqtn uequn veqvn* **by** (*metis (mono-tags, lifting) int-ops(2) int-ops(4) int-ops(7)*)
numeral-Bit0 numeral-code(1) plus-1-eq-Suc zdiv-int
hence $N = (m*(sn^2-sn) \text{ div } 2 + sn) + (m*(tn^2-tn) \text{ div } 2 + tn) + (m*(un^2-un) \text{ div } 2 + un) + (m*(vn^2-vn) \text{ div } 2 + vn) + r$
using *sn-def tn-def un-def stuv int-nat-eq int-ops(5)* **by** *presburger*
hence $N = (m*(sn^2-sn) \text{ div } 2 + sn) + (m*(tn^2-tn) \text{ div } 2 + tn) + (m*(un^2-un) \text{ div } 2 + un) + (m*(vn^2-vn) \text{ div } 2 + vn) + r$
using *vn-def stuv* **by** (*smt (verit, del-insts) Num.of-nat-simps(4) int-nat-eq of-nat-eq-iff*)
hence $N = (m* sn*(sn-1) \text{ div } 2 + sn) + (m*tn*(tn-1) \text{ div } 2 + tn) + (m*un*(un-1) \text{ div } 2 + un) + (m* vn*(vn-1) \text{ div } 2 + vn) + r$
by (*smt (verit, ccfv-threshold) more-arith-simps(11) mult.right-neutral power2-eq-square right-diff-distrib*)

hence $N\text{-expr4}:N = \text{polygonal-number } m \text{ sn} + \text{polygonal-number } m \text{ tn} + \text{polygonal-number } m \text{ un} + \text{polygonal-number } m \text{ vn} + r$

using *Polygonal-Number-Theorem-Gauss.polygonal-number-def* **by** *presburger*

define T **where** $T\text{-def}:T = [\text{polygonal-number } m \text{ sn}, \text{polygonal-number } m \text{ tn}, \text{polygonal-number } m \text{ un}, \text{polygonal-number } m \text{ vn}]$

define ones **where** $\text{ones-def}:\text{ones} = \text{replicate } r \text{ (1::nat)}$

define zeros **where** $\text{zeros-def}:\text{zeros} = \text{replicate } (m+1-4-r) \text{ (0::nat)}$

define final **where** $\text{final-def}:\text{final} = T@\text{ones}@\text{zeros}$

have $m+1-4-r \geq 0$ **using** *assms(1)* $b-r$ **by** *force*

hence $4+r+(m+1-4-r) = m+1$ **using** *assms(1)* $b-r$ **by** *force*

have $\text{length final} = 4+r+(m+1-4-r)$ **using** final-def $T\text{-def}$ ones-def zeros-def **by** *auto*

hence $\text{final-length}:\text{length final} = m+1$ **using** $\langle 4+r+(m+1-4-r) = m+1 \rangle$ **by** *simp*

have $T\text{-sum}:\text{sum-list } T = \text{polygonal-number } m \text{ sn} + \text{polygonal-number } m \text{ tn} + \text{polygonal-number } m \text{ un} + \text{polygonal-number } m \text{ vn}$ **by** (*simp add: T-def*)

have $\text{ones-sum}:\text{sum-list ones} = r$ **using** ones-def **by** (*simp add: sum-list-replicate*)

have $\text{zeros-sum}:\text{sum-list zeros} = 0$ **using** zeros-def **by** *simp*

have $\text{sum-list final} = \text{sum-list } T + \text{sum-list ones} + \text{sum-list zeros}$ **using** final-def **by** *simp*

hence $\text{final-sum}:\text{sum-list final} = N$ **using** $N\text{-expr4}$ **by** (*simp add: T-sum ones-sum zeros-sum*)

have $\text{final-0th}:\text{final! } 0 = \text{polygonal-number } m \text{ sn}$ **using** final-def $T\text{-def}$ **by** *simp*

have $\text{final-1st}:\text{final! } 1 = \text{polygonal-number } m \text{ tn}$ **using** final-def $T\text{-def}$ **by** *simp*

have $\text{final-2nd}:\text{final! } 2 = \text{polygonal-number } m \text{ un}$ **using** final-def $T\text{-def}$ **by** *simp*

have $\text{final-3rd}:\text{final! } 3 = \text{polygonal-number } m \text{ vn}$ **using** final-def $T\text{-def}$ **by** *simp*

have $\text{first-four}:\forall k \leq 3. \exists a. \text{final! } k = \text{polygonal-number } m \text{ a}$ **using** final-0th final-1st final-2nd final-3rd

by (*metis Suc-eq-plus1 add-leD2 arith-simps(50) le-simps(2) numeral-Bit0 numeral-Bit1*)

numeral-One verit-comp-simplify1(3) verit-la-disequality)

have $\text{length } T = 4$ **using** $T\text{-def}$ **by** *simp*

have $\forall k < \text{length } (\text{ones}@\text{zeros}). (\text{ones}@\text{zeros})! k = 1 \vee (\text{ones}@\text{zeros})! k = 0$ **using** ones-def zeros-def

by (*simp add: nth-append*)

hence $\text{final! } k = 1 \vee \text{final! } k = 0$ **if** $k \geq 4 \wedge k < (\text{length final})$ **for** k

using $\langle \text{length } T = 4 \rangle$ final-def **that** **by** (*metis add-less-cancel-left le-add-diff-inverse length-append nth-append verit-comp-simplify1(3)*)

hence $\text{other-terms}:\forall k \in \{4..m\}. \text{final! } k = 0 \vee \text{final! } k = 1$ **using** final-length

by (*metis Suc-eq-plus1 atLeastAtMost-iff le-simps(2)*)

show *?thesis* **using** final-length final-sum first-four other-terms **by** *auto*
qed

theorem *Strong-Form-of-Cauchy-Polygonal-Number-Theorem-2:*

fixes $N :: \text{nat}$

assumes $N \geq 324$

shows $\exists p1\ p2\ p3\ p4\ r :: \text{nat}. N = p1 + p2 + p3 + p4 + r \wedge (\exists k1. p1 = \text{polygonal-number } 3\ k1) \wedge (\exists k2. p2 = \text{polygonal-number } 3\ k2) \wedge (\exists k3. p3 = \text{polygonal-number } 3\ k3) \wedge (\exists k4. p4 = \text{polygonal-number } 3\ k4) \wedge (r = 0 \vee r = 1)$

proof –

define L **where** $L\text{-def}: L = (2/3 + \text{sqrt}(8*N/3 - 8)) - (1/2 + \text{sqrt}(6*N/3 - 3))$

from $\text{assms } L\text{-def}$ **have** $L > 4$ **using** *interval-length-greater-than-four*

apply –

apply(*rule interval-length-greater-than-four*[**where** $N = \text{of-nat } N$ **and** $m = \text{of-nat } 3$])

by *auto*

define $c1$ **where** $c1\text{-def}: c1 = \lceil 1/2 + \text{sqrt}(6*N/3 - 3) \rceil$

define $c2$ **where** $c2\text{-def}: c2 = c1 + 1$

define $c3$ **where** $c3\text{-def}: c3 = c1 + 2$

define $c4$ **where** $c4\text{-def}: c4 = c1 + 3$

from $\langle L > 4 \rangle$ $c1\text{-def } c2\text{-def } c3\text{-def } c4\text{-def } L\text{-def}$ **have** $c4 < (2/3 + \text{sqrt}(8*N/3 - 8))$ **by** *linarith*

define Nn **where** $Nn = \text{int } N$

have $c4 < (2/3 + \text{sqrt}(8*Nn/3 - 8))$ **using** $Nn\text{-def } \langle c4 < (2/3 + \text{sqrt}(8*N/3 - 8)) \rangle$ **by** *simp*

have $Nn3: (Nn-3)^2 - (\text{sqrt}(8*Nn/3 - 8))^2 = Nn^2 - 3*Nn - 3*Nn + 9 - (\text{sqrt}(8*Nn/3 - 8))^2$

using $\text{assms } Nn\text{-def}$ *power2-diff* **by** (*simp add: power2-eq-square algebra-simps*)

have $(Nn-3)^2 - (\text{sqrt}(8*Nn/3 - 8))^2 = Nn^2 - 3*Nn - 3*Nn + 9 - (8*Nn/3 - 8)$ **using** $\text{assms } Nn\text{-def } Nn3$ **by** *fastforce*

hence $(Nn-3)^2 - (\text{sqrt}(8*Nn/3 - 8))^2 = Nn^2 - 6*Nn + 9 - 8*Nn/3 + 8$ **by** *linarith*

hence $Nn4: (Nn-3)^2 - (\text{sqrt}(8*Nn/3 - 8))^2 = Nn*(Nn-26/3) + 17$ **by** (*simp add: Rings.ring-distrib(4) power2-eq-square*)

have $Nn*(Nn-26/3) + 17 > 17$ **using** $\text{assms } Nn\text{-def}$ **by** *auto*

hence $(Nn-3)^2 - (\text{sqrt}(8*Nn/3 - 8))^2 > 0$ **using** $Nn4$ **by** *auto*

hence $Nn-3 > \text{sqrt}(8*Nn/3 - 8)$ **using** $\text{assms } Nn\text{-def}$ **by** (*simp add: real-less-lsqrt*)

hence $Nn-2 > \text{sqrt}(8*Nn/3 - 8) + 2/3$ **by** *linarith*

hence $N > c4$ **using** $Nn\text{-def } \langle c4 < (2/3 + \text{sqrt}(8*Nn/3 - 8)) \rangle$ **by** *simp*

have $N/3 \geq 108$ **using** assms **using** *le-divide-eq* **by** *fastforce*

hence $\text{sqrt}(6*N/3 - 3) \geq 1$ **by** *simp*

hence $1/2 + \text{sqrt}(6*N/3 - 3) \geq 1$ **by** *linarith*

hence $c1 \geq 1$ **using** $c1\text{-def}$ **by** *simp*

obtain $b1\ b2$ **where** $b\text{properties}: \{b1, b2\} \subseteq \{c1, c2, c3, c4\} \wedge (b2 = b1 + 2) \wedge \text{odd } b1$

```

using two-consec-odd c1-def c2-def c3-def c4-def by (metis (no-types, opaque-lifting)
Groups.add-ac(2)
empty-subsetI even-plus-one-iff insert-commute insert-mono nat-arith.add1 numeral.simps(2)
numeral.simps(3))
have b1andb2:odd b1  $\wedge$  b2 = b1+2 using bproperties by auto
have b1pos:b1  $\geq$  1 using  $\langle$ c1 $\geq$ 1 $\rangle$  c2-def c3-def c4-def bproperties by auto
hence b2pos:b2  $\geq$  3 using bproperties by simp
have b2odd:odd b2 using bproperties by simp
define b1n where b1n = nat b1
define b2n where b2n = nat b2

from b1n-def b1pos have b1n mod 3 = b1 mod 3 using int-ops(9) by force
from b2n-def b2pos have b2n mod 3 = b2 mod 3 using int-ops(9) by force

have b-and-r: $\exists$  b r::nat. [N = b+r] (mod 3)  $\wedge$  (b = b1n  $\vee$  b = b2n)  $\wedge$  (r = 0  $\vee$ 
r = 1)
proof –
have case1: $\exists$  b r::nat. [N = b+r] (mod 3)  $\wedge$  (b = b1n  $\vee$  b = b2n)  $\wedge$  (r = 0  $\vee$ 
r = 1)
if asm1:b1 mod 3 = 0
proof –
have b1n mod 3 = 0 using asm1  $\langle$ b1n mod 3 = b1 mod 3 $\rangle$  by simp
hence b2n mod 3 = 2 using  $\langle$ b2n mod 3 = b2 mod 3 $\rangle$  bproperties asm1 by
fastforce
have case1-1:[0 = b1n+0] (mod 3) using  $\langle$ b1n mod 3 = 0 $\rangle$ 
by (metis mod-0 nat-arith.rule0 unique-euclidean-semiring-class.cong-def)
have case1-2:[1 = b1n+1] (mod 3) using  $\langle$ b1n mod 3 = 0 $\rangle$ 
by (metis  $\langle$ [0 = b1n + 0] (mod 3) $\rangle$  add commute cong-add-lcancel-0-nat
cong-sym)
have case1-3:[2 = b2n+0] (mod 3) using  $\langle$ b2n mod 3 = 2 $\rangle$ 
by (simp add: unique-euclidean-semiring-class.cong-def)
have  $\forall$  N::nat. N mod 3 = 0  $\vee$  N mod 3  $\geq$  1 by linarith
hence  $\forall$  N::nat. N mod 3 = 0  $\vee$  N mod 3 = 1  $\vee$  N mod 3 = 2 by linarith
hence  $\forall$  N.  $\exists$  b r::nat. [N = b+r] (mod 3)  $\wedge$  (b = b1n  $\vee$  b = b2n)  $\wedge$  (r = 0
 $\vee$  r = 1)
if asm1:b1 mod 3 = 0 using case1-1 case1-2 case1-3 by (metis cong-mod-left)
thus ?thesis using asm1 by auto
qed

have case2: $\exists$  b r::nat. [N = b+r] (mod 3)  $\wedge$  (b = b1n  $\vee$  b = b2n)  $\wedge$  (r = 0  $\vee$ 
r = 1)
if asm2:b1 mod 3 = 1
proof –
have b1n mod 3 = 1 using asm2  $\langle$ b1n mod 3 = b1 mod 3 $\rangle$  by simp
hence b2n mod 3 = 0 using  $\langle$ b2n mod 3 = b2 mod 3 $\rangle$  bproperties asm2
by (smt (verit, best) Euclidean-Rings.pos-mod-bound Euclidean-Rings.pos-mod-sign
int-ops(1) mod-diff-eq mod-pos-pos-trivial of-nat-eq-iff)
have case2-1:[0 = b2n+0] (mod 3) using  $\langle$ b2n mod 3 = 0 $\rangle$ 
by (metis mod-0 nat-arith.rule0 unique-euclidean-semiring-class.cong-def)

```

have case2-2:[1 = b1n+0] (mod 3) **using** ⟨b1n mod 3 = 1⟩
by (simp add: unique-euclidean-semiring-class.cong-def)
have case2-3:[2 = b1n+1] (mod 3) **using** ⟨b1n mod 3 = 1⟩
by (metis case2-2 cong-add-rcancel-nat nat-1-add-1 nat-arith.rule0)
have $\forall N::\text{nat}. N \bmod 3 = 0 \vee N \bmod 3 \geq 1$ **by** linarith
hence $\forall N::\text{nat}. N \bmod 3 = 0 \vee N \bmod 3 = 1 \vee N \bmod 3 = 2$ **by** linarith
hence $\forall N. \exists b r::\text{nat}. [N = b+r] \pmod{3} \wedge (b = b1n \vee b = b2n) \wedge (r = 0$
 $\vee r = 1)$
if asm2:b1 mod 3 = 1 **using** case2-1 case2-2 case2-3 **by** (metis cong-mod-left)
thus ?thesis **using** asm2 **by** auto
qed

have case3: $\exists b r::\text{nat}. [N = b+r] \pmod{3} \wedge (b = b1n \vee b = b2n) \wedge (r = 0 \vee$
 $r = 1)$
if asm3:b1 mod 3 = 2
proof –
have b1n mod 3 = 2 **using** asm3 ⟨b1n mod 3 = b1 mod 3⟩ **by** simp
have (b1+2) mod 3 = (2+2) mod 3 **using** asm3 **by** (metis Groups.add-ac(2)
mod-add-right-eq)
hence b2n mod 3 = 1 **using** ⟨b2n mod 3 = b2 mod 3⟩ bproperties **by** simp
have case3-1:[0 = b1n+1] (mod 3) **using** ⟨b1n mod 3 = 2⟩
by (metis One-nat-def add.commute mod-0 mod-add-right-eq mod-self
nat-1-add-1 numeral-3-eq-3
plus-1-eq-Suc unique-euclidean-semiring-class.cong-def)
have case3-2:[1 = b2n+0] (mod 3) **using** ⟨b2n mod 3 = 1⟩
by (simp add: unique-euclidean-semiring-class.cong-def)
have case3-3:[2 = b1n+0] (mod 3) **using** ⟨b1n mod 3 = 2⟩
by (simp add: unique-euclidean-semiring-class.cong-def)
have $\forall N::\text{nat}. N \bmod 3 = 0 \vee N \bmod 3 \geq 1$ **by** linarith
hence $\forall N::\text{nat}. N \bmod 3 = 0 \vee N \bmod 3 = 1 \vee N \bmod 3 = 2$ **by** linarith
hence $\forall N. \exists b r::\text{nat}. [N = b+r] \pmod{3} \wedge (b = b1n \vee b = b2n) \wedge (r = 0$
 $\vee r = 1)$
if asm3:b1 mod 3 = 2 **using** case3-1 case3-2 case3-3 **by** (metis cong-mod-left)
thus ?thesis **using** asm3 **by** auto
qed

have b1 mod 3 = 0 \vee b1 mod 3 = 1 \vee b1 mod 3 = 2 **by** auto
thus ?thesis **using** case1 case2 case3 **by** auto
qed

obtain b r **where** b-r:[N = b+r] (mod 3) \wedge (b = b1n \vee b = b2n) \wedge (r = 0 \vee
r = 1)
using b-and-r **by** auto

have bpos:b \geq 1 **using** b1pos b2pos b-r b1n-def b2n-def **by** auto
have bodd:odd b
using b-r bproperties **by** (metis b1n-def b2n-def b2odd bpos even-nat-iff nat-eq-iff2
rel-simps(45))

```

define a where a-def:a = b + 2*(N - b - r) div 3
have int b1n = b1 using b1n-def b1pos by linarith
have int b2n = b2 using b2n-def b2pos by linarith
have m-div-num:3 dvd (N - b - r) using b-r
  by (metis cong-altdef-nat diff-diff-left diff-is-0-eq' dvd-0-right nat-le-linear)
hence a-def1:a = b + 2*(N - b - r)/3 using a-def m-div-num real-of-nat-div by
auto
from ⟨N > c4⟩ have N > b using b-r bproperties b1n-def b2n-def
  by (smt (verit, del-insts) ⟨int b1n = b1⟩ ⟨int b2n = b2⟩ c2-def c3-def c4-def
empty-iff insert-iff insert-subset of-nat-less-imp-less)
hence (N - b - r)/3 = (N - r)/3 - b/3 using ⟨b < N⟩ b-r by force
hence a = b - b*2/3 + 2*(N - r)/3 using a-def1 by linarith
hence a-def3:a = b*(1 - 2/3) + 2*(N - r)/3 by simp

have size1:b*(1 - 2/3) > 0 using bpos by simp
have N-r > 0 using b-r assms by auto
hence size2:2*(N - r)/3 > 0 using assms(1) by simp
have apos:a ≥ 1 using size1 size2 a-def3 by linarith

have odd (b + 2*(N - b - r) div 3) using m-div-num b-r b2odd bproperties by
(simp add: bodd mult-2)
hence aodd:odd a using a-def by simp
from a-def1 have a - b = 2*(N - b - r)/3 by simp
hence (a - b)/2 = (N - b - r)/3 by simp
hence 3*(a - b)/2 = N - b - r by simp
have N-b-r ≥ 0 using b-r by simp
hence N-expr:N = r + b + 3*(a - b)/2 using ⟨N - b - r ≥ 0⟩ ⟨b < N⟩ b-r ⟨real (3
* (a - b)) / 2 = real (N - b - r)⟩ by linarith
from a-def ⟨N - b - r ≥ 0⟩ have a ≥ b using a-def le-add1 by blast

have b1 ≥ c1 using bproperties c2-def c3-def c4-def by force
hence b1 ≥ 1/2 + sqrt (6*N/3 - 3) using c1-def using ceiling-le-iff by blast
hence b1ngreater:b1n ≥ 1/2 + sqrt (6*N/3 - 3) using b1n-def by simp
hence b2ngreater:b2n ≥ 1/2 + sqrt (6*N/3 - 3) using bproperties b1n-def
b2n-def by linarith
hence b-ineq1:b ≥ 1/2 + sqrt (6*N/3 - 3) using b-r b1ngreater by auto

have b2 ≤ c4 using bproperties c1-def c2-def c3-def c4-def by fastforce
hence b2 ≤ (2/3 + sqrt (8*N/3 - 8))
  using ⟨real-of-int c4 < 2 / 3 + sqrt (real (8 * N) / 3 - 8)⟩ by linarith
hence b2nsmaller:b2n ≤ (2/3 + sqrt (8*N/3 - 8)) using b2n-def by (metis
⟨int b2n = b2⟩ of-int-of-nat-eq)
hence b1n ≤ (2/3 + sqrt (8*N/3 - 8)) using b1n-def bproperties using ⟨int
b2n = b2⟩ by linarith
hence b-ineq2:b ≤ (2/3 + sqrt (8*N/3 - 8)) using b-r b2nsmaller by auto

define Nr where Nr = real-of-nat N
define ar where ar = real-of-int a
define br where br = real-of-int b

```

```

define rr where rr = real-of-nat r
define m where m = real-of-nat 3
from assms have  $N \geq 2 * m$  using m-def by simp
then have  $Nr \geq 2 * m$  using Nr-def  $\langle N \geq 2 * m \rangle$  by auto
moreover have  $br \geq 0$  using br-def bpos by auto
moreover have  $ar \geq 0$  using ar-def apos by auto
moreover have  $rr \geq 0$  using rr-def b-r by auto
moreover have  $m \geq 3$  using m-def by auto
moreover have  $m > rr$  using m-def rr-def b-r by auto
moreover have  $Nr = m * (ar - br) / 2 + br + rr$  using Nr-def ar-def br-def N-expr
rr-def m-def  $\langle a \geq b \rangle$  by auto
moreover have  $1/2 + \text{sqrt}(6 * Nr / m - 3) \leq br \wedge br \leq 2/3 + \text{sqrt}(8 * Nr / m - 8)$  using
Nr-def br-def b-ineq1 b-ineq2 m-def by auto
ultimately have  $br^2 < 4 * ar \wedge 3 * ar < br^2 + 2 * br + 4$  using Cauchy-lemma by
auto
hence real-ineq:  $(\text{real-of-int } b)^2 < 4 * (\text{real-of-int } a) \wedge 3 * (\text{real-of-int } a) < (\text{real-of-int } b)^2 + 2 * (\text{real-of-int } b) + 4$ 
using br-def ar-def by auto
hence nat-ineq1:  $b^2 < 4 * a$  using br-def by (smt (verit, del-insts) Num.of-nat-simps(4)
mult.commute mult-2-right nat-distrib(1) numeral-Bit0 of-int-of-nat-eq of-nat-less-of-nat-power-cancel-iff)
from real-ineq have nat-ineq2:  $3 * a < b^2 + 2 * b + 4$  using ar-def br-def of-nat-less-iff
by fastforce

obtain s t u v where  $stuv: s \geq 0 \wedge t \geq 0 \wedge u \geq 0 \wedge v \geq 0 \wedge \text{int } a = s^2 + t^2 + u^2 + v^2 \wedge$ 
 $\text{int } b = s + t + u + v$  using apos bpos aodd bodd nat-ineq1 nat-ineq2 four-nonneg-int-sum
by presburger
have a-expr:  $a = s^2 + t^2 + u^2 + v^2$  using apos stuv by linarith
have b-expr:  $b = s + t + u + v$  using bpos stuv by linarith

have  $N = r + (s + t + u + v) + 3 * (a - (s + t + u + v)) / 2$  using b-expr N-expr
by (metis Num.of-nat-simps(4) Num.of-nat-simps(5)  $\langle b \leq a \rangle$  of-int-of-nat-eq
of-nat-diff of-nat-numeral)
hence  $N = 3/2 * (s^2 - s + t^2 - t + u^2 - u + v^2 - v) + r + (s + t + u + v)$  using a-expr
by simp
hence N-expr2:  $N = 3/2 * (s^2 - s) + 3/2 * (t^2 - t) + 3/2 * (u^2 - u) + 3/2 * (v^2 - v) + r + (s + t + u + v)$ 
by (metis (no-types, opaque-lifting) add-diff-eq nat-distrib(2) of-int-add)

have s-div2:  $3/2 * (s^2 - s) = 3 * (s^2 - s) \text{ div } 2$  using real-of-int-div by auto
have t-div2:  $3/2 * (t^2 - t) = 3 * (t^2 - t) \text{ div } 2$  using real-of-int-div by auto
have u-div2:  $3/2 * (u^2 - u) = 3 * (u^2 - u) \text{ div } 2$  using real-of-int-div by auto
have v-div2:  $3/2 * (v^2 - v) = 3 * (v^2 - v) \text{ div } 2$  using real-of-int-div by auto
have N-expr3:  $N = (3 * (s^2 - s) \text{ div } 2 + s) + (3 * (t^2 - t) \text{ div } 2 + t) + (3 * (u^2 - u) \text{ div } 2 + u) + (3 * (v^2 - v) \text{ div } 2 + v) + r$ 
using N-expr2 s-div2 t-div2 u-div2 v-div2 by simp

define sn where sn = nat s
define tn where tn = nat t

```

```

define un where un = nat u
define vn where vn = nat v
have seqsn: $s^2 - s = sn^2 - sn$  using stuv sn-def
  by (metis int-nat-eq le-refl of-nat-diff of-nat-power power2-nat-le-imp-le)
have teqtn: $t^2 - t = tn^2 - tn$  using stuv tn-def
  by (metis int-nat-eq le-refl of-nat-diff of-nat-power power2-nat-le-imp-le)
have uequn: $u^2 - u = un^2 - un$  using stuv un-def
  by (metis int-nat-eq le-refl of-nat-diff of-nat-power power2-nat-le-imp-le)
have veqvn: $v^2 - v = vn^2 - vn$  using stuv vn-def
  by (metis int-nat-eq le-refl of-nat-diff of-nat-power power2-nat-le-imp-le)

from N-expr3 have
   $N = (3*(sn^2 - sn) \text{ div } 2 + s) + (3*(tn^2 - tn) \text{ div } 2 + t) + (3*(un^2 - un) \text{ div } 2 + u) + (3*(vn^2 - vn) \text{ div } 2 + v) + r$ 
  using seqsn teqtn uequn veqvn
  by (metis (mono-tags, lifting) Num.of-nat-simps(5) of-nat-numeral zdiv-int)
  hence  $N = (3*(sn^2 - sn) \text{ div } 2 + sn) + (3*(tn^2 - tn) \text{ div } 2 + tn) + (3*(un^2 - un) \text{ div } 2 + un) + (3*(vn^2 - vn) \text{ div } 2 + v) + r$ 
  using sn-def tn-def un-def stuv int-nat-eq int-ops(5) by presburger
  hence  $N = (3*(sn^2 - sn) \text{ div } 2 + sn) + (3*(tn^2 - tn) \text{ div } 2 + tn) + (3*(un^2 - un) \text{ div } 2 + un) + (3*(vn^2 - vn) \text{ div } 2 + vn) + r$ 
  using vn-def stuv by (smt (verit, del-insts) Num.of-nat-simps(4) int-nat-eq of-nat-eq-iff)
  hence  $N = (3*sn*(sn-1) \text{ div } 2 + sn) + (3*tn*(tn-1) \text{ div } 2 + tn) + (3*un*(un-1) \text{ div } 2 + un) + (3*vn*(vn-1) \text{ div } 2 + vn) + r$ 
  by (smt (verit, ccfv-threshold) more-arith-simps(11) mult.right-neutral power2-eq-square right-diff-distrib)
  hence N-expr4: $N = \text{polygonal-number } 3 \text{ } sn + \text{polygonal-number } 3 \text{ } tn + \text{polygonal-number } 3 \text{ } un + \text{polygonal-number } 3 \text{ } vn + r$ 
  using Polygonal-Number-Theorem-Gauss.polygonal-number-def by presburger

define p1 where p1 = polygonal-number 3 sn
define p2 where p2 = polygonal-number 3 tn
define p3 where p3 = polygonal-number 3 un
define p4 where p4 = polygonal-number 3 vn
have N-expr5: $N = p1 + p2 + p3 + p4 + r$  using N-expr4 p1-def p2-def p3-def p4-def by auto
  thus ?thesis using p1-def p2-def p3-def p4-def b-r by blast
qed
end

```

2.3 Legendre's Polygonal Number Theorem

We will use the definition of the polygonal numbers from the Gauss Theorem theory file which also imports the Three Squares Theorem AFP entry [1].

```

theory Polygonal-Number-Theorem-Legendre
  imports Polygonal-Number-Theorem-Gauss
begin

```

This lemma shows that under certain conditions, an integer N can be written as the sum of four polygonal numbers.

lemma *sum-of-four-polygonal-numbers*:

```

fixes  $N\ m :: nat$ 
fixes  $b :: int$ 
assumes  $m \geq 3$ 
assumes  $N \geq 2*m$ 
assumes  $[N = b] \pmod m$ 
assumes odd-b:  $odd\ b$ 
assumes  $b \in \{1/2 + \sqrt{6*N/m - 3} .. 2/3 + \sqrt{8*N/m - 8}\}$ 
assumes  $N \geq 9$ 
shows  $\exists k1\ k2\ k3\ k4. N = \text{polygonal-number } m\ k1 + \text{polygonal-number } m\ k2 +$ 
 $\text{polygonal-number } m\ k3 + \text{polygonal-number } m\ k4$ 

```

proof –

```

define  $I$  where  $I = \{1/2 + \sqrt{6*N/m - 3} .. 2/3 + \sqrt{8*N/m - 8}\}$ 
from assms(5)  $I$ -def have  $b \in I$  by auto

```

```

define  $a::int$  where  $a$ -def:  $a = 2*(N-b) \text{ div } m + b$ 

```

```

have  $m \text{ dvd } (N-b)$  using assms(3)

```

```

  by (smt (verit, ccfv-threshold) cong-iff-dvd-diff zdvd-zdiffD)

```

```

hence  $even\ (2*(N-b) \text{ div } m)$ 

```

```

  by (metis div-mult-swap dvd-triv-left)

```

```

hence  $odd\ a$  using  $a$ -def assms(3) odd-b by auto

```

```

from assms(1) have  $m^3 \geq m$ 

```

```

  by (simp add: power3-eq-cube)

```

```

hence  $N \geq 2 * m$  using assms(1,2) by simp

```

```

from assms(1) have  $m$ -pos:  $m > 0$  by auto

```

```

have  $N \geq b$ 

```

proof –

```

from assms(1) have  $m \geq 1$  by auto

```

```

hence  $1/m \leq 1$  using  $m$ -pos by auto

```

```

moreover have  $N > 0$  using  $\langle N \geq 2 * m \rangle$   $m$ -pos by auto

```

```

ultimately have  $N/m \leq N$ 

```

```

  using divide-less-eq-1 less-eq-real-def by fastforce

```

```

hence  $\sqrt{8*N/m - 8} \leq \sqrt{8*(N-1)}$  by auto

```

```

from assms(1) have  $m^3 \geq 3*3*(3::real)$ 

```

```

  by (metis numeral-le-real-of-nat-iff numeral-times-numeral power3-eq-cube
power-mono zero-le-numeral)

```

```

from  $\langle N \geq 9 \rangle$  have  $N-1 \geq 8$  by auto

```

```

hence  $(N-1)^2 \geq 8*(N-1)$  using  $\langle N > 0 \rangle$  by (simp add: power2-eq-square)

```

```

hence  $(N-1) \geq \sqrt{8*(N-1)}$  using  $\langle N > 0 \rangle$ 

```

```

by (metis of-nat-0-le-iff of-nat-mono of-nat-power real-sqrt-le-mono real-sqrt-pow2
real-sqrt-power)

```

```

hence  $N - (1::real) - \sqrt{8*N/m - 8} \geq 0$ 

```

```

  using  $\langle \sqrt{\text{real } (8 * N) / \text{real } m - 8} \leq \sqrt{\text{real } (8 * (N - 1))} \rangle$   $\langle 9 \leq$ 
 $N \rangle$  by linarith

```

```

hence expr-pos:  $N - (2/3::real) - \sqrt{8*N/m - 8} \geq 0$  by auto

```

```

have  $b \leq 2/3 + \sqrt{8*N/m - 8}$  using  $\langle b \in I \rangle$   $I$ -def by auto

```

```

hence  $N - b \geq N - (2/3 + \sqrt{8*N/m - 8})$  by auto

```


hence $N - b \geq 0$
using *expr-pos of-int-0-le-iff* **by** *auto*
thus *?thesis* **by** *auto*
qed
from $\langle N \geq 2 * m \rangle$ *m-pos* **have** $6*N/m - 3 \geq 0$ **by** (*simp add: mult-imp-le-div-pos*)
hence $1/2 + \text{sqrt}(6*N/m - 3) > 0$
by (*smt (verit, del-insts) divide-le-0-1-iff real-sqrt-ge-zero*)
with $\langle b \in I \rangle$ *assms(3) I-def* **have** $b \geq 1$ **by** *auto*
hence *b-pos: b ≥ 0* **by** *auto*
from $\langle b \in I \rangle$ **have** *b-in-I: (1/2::real) + sqrt(6* real N / real m - 3) ≤ b ∧ b*
 $\leq (2/3::real) + \text{sqrt}(8 * \text{real } N/\text{real } m - 8)$ **unfolding** *I-def* **by** *auto*
from *b-pos* $\langle N \geq b \rangle$ *a-def* **have** *a-pos: a ≥ 0*
by (*smt (verit) m-pos of-nat-0-less-iff pos-imp-zdiv-neg-iff*)
hence $a \geq 1$
by (*smt (verit) <odd a> dvd-0-right*)
have $a - b = 2*(N-b) \text{ div } m$ **using** *a-def* **by** *auto*
from $\langle \text{int } m \text{ dvd } (\text{int } N - b) \rangle$ **have** $m \text{ dvd } 2*(N-b)$ **by** *fastforce*
have $a = 2*(N-b)/m + b$ **using** *a-def m-pos*
using $\langle \text{int } m \text{ dvd } 2 * (\text{int } N - b) \rangle$ **by** *fastforce*
hence $a = 2*N/m - 2*b/m + b$
by (*simp add: assms diff-divide-distrib of-nat-diff*)
hence $(2::\text{real})*N/m = a + 2*b/m - b$ **by** *auto*
hence $(2::\text{real})*N = (a + 2*b/m - b)*m$
using *m-pos* **by** (*simp add: divide-eq-eq*)
hence $(2::\text{real})*N = m*(a-b) + 2*b$
using $\langle \text{int } m \text{ dvd } 2 * (\text{int } N - b) \rangle$ *a-def* **by** *auto*
hence $N = m*(a-b)/2 + b$ **by** *auto*
hence *N-expr: real N = real m * (of-int a - of-int b) / 2 + of-int b* **by** *auto*
have *even (a-b)* **using** $\langle \text{odd } a \rangle \langle \text{odd } b \rangle$ **by** *auto*
hence $2 \text{ dvd } m*(a-b)$ **by** *auto*
hence *N-expr2: N = m*(a-b) div 2 + b* **using** $\langle N = m*(a-b)/2 + b \rangle$ **by**
linarith
define *Nr* **where** *Nr = real-of-nat N*
define *mr* **where** *mr = real m*
define *ar* **where** *ar = real-of-int a*
define *br* **where** *br = real-of-int b*
from *assms(1)* **have** $mr \geq 3$ **using** *mr-def* **by** *auto*
moreover **have** $Nr \geq 2*mr$ **using** *Nr-def mr-def* $\langle N \geq 2 * m \rangle$ **by** *auto*
moreover **have** $br \geq 0$ **using** *br-def b-pos* **by** *auto*
moreover **have** $mr > 0$ **using** *mr-def m-pos* **by** *auto*
moreover **have** $ar \geq 0$ **using** *ar-def* $\langle a \geq 0 \rangle$ **by** *auto*
moreover **have** $Nr = mr*(ar-br)/2 + br$ **using** *Nr-def mr-def ar-def br-def*
N-expr **by** *auto*
moreover **have** $1/2 + \text{sqrt}(6*Nr/mr-3) \leq br \wedge br \leq 2/3 + \text{sqrt}(8*Nr/mr-8)$
using *Nr-def mr-def br-def b-in-I* **by** *auto*
ultimately **have** $br^2 < 4*ar \wedge 3*ar < br^2 + 2*br + 4$ **using** *Cauchy-lemma-r-eq-zero*
by *auto*
hence *real-ineq: (real-of-int b)^2 < 4*(real-of-int a) ∧ 3*(real-of-int a) < (real-of-int*
 $b)^2 + 2*(\text{real-of-int } b) + 4$

using *br-def ar-def by auto*
hence *int-ineq1: $b^2 < 4 * a$ using of-int-less-iff by fastforce*
from *real-ineq have int-ineq2: $3 * a < b^2 + 2 * b + 4$ using of-int-less-iff by fastforce*

define *an:: nat where an = nat a*
from *a-pos have an = a unfolding an-def by auto*
define *bn:: nat where bn = nat b*
from *b-pos have bn = b unfolding bn-def by auto*
have *an ≥ 1 using ⟨int an = a⟩ ⟨a ≥ 1⟩ by auto*
moreover *have bn ≥ 1 using ⟨int bn = b⟩ ⟨b ≥ 1⟩ by auto*
moreover *have odd an using ⟨odd a⟩ ⟨int an = a⟩ by auto*
moreover *have odd bn using ⟨odd b⟩ ⟨int bn = b⟩ by auto*
moreover *have $bn^2 < 4 * an$ using int-ineq1 ⟨int an = a⟩ ⟨int bn = b⟩*
using *of-nat-less-iff by fastforce*
moreover *have $3 * an < bn^2 + 2 * bn + 4$ using int-ineq2 ⟨int an = a⟩*
⟨int bn = b⟩
using *of-nat-less-iff by fastforce*
ultimately *have $\exists s t u v :: int. s \geq 0 \wedge t \geq 0 \wedge u \geq 0 \wedge v \geq 0 \wedge an = s^2 + t^2 + u^2 + v^2 \wedge$*
 $bn = s + t + u + v$ using four-nonneg-int-sum by auto
hence *$\exists s t u v :: int. s \geq 0 \wedge t \geq 0 \wedge u \geq 0 \wedge v \geq 0 \wedge a = s^2 + t^2 + u^2 + v^2 \wedge$*
 $b = s + t + u + v$ using ⟨int an = a⟩ ⟨int bn = b⟩ by auto
then obtain *$s t u v :: int$ where *stuv*: $s \geq 0 \wedge t \geq 0 \wedge u \geq 0 \wedge v \geq 0 \wedge a = s^2 + t^2 + u^2 + v^2 \wedge$*
 $b = s + t + u + v$ by auto
hence *$N = (m * (s^2 + t^2 + u^2 + v^2 - s - t - u - v) \text{ div } 2) + s + t + u + v$ using*
 $N\text{-expr2}$ by (smt (verit, ccfv-threshold))
hence *$N = (m * (s^2 - s + t^2 - t + u^2 - u + v^2 - v) \text{ div } 2) + s + t + u + v$ by (smt*
(verit, ccfv-SIG))
hence *$N = (m * (s * (s - 1) + t * (t - 1) + u * (u - 1) + v * (v - 1))) \text{ div } 2 + s + t + u + v$ by (simp add: power2-eq-square algebra-simps)*
hence *previous-step: $N = (m * s * (s - 1) + m * t * (t - 1) + m * u * (u - 1) + m * v * (v - 1)) \text{ div } 2 + s + t + u + v$ by (simp add: algebra-simps)*
moreover *have 2 dvd $m * s * (s - 1)$ by simp*
moreover *have 2 dvd $m * t * (t - 1)$ by simp*
moreover *have 2 dvd $m * u * (u - 1)$ by simp*
moreover *have 2 dvd $m * v * (v - 1)$ by simp*
ultimately *have $N = m * s * (s - 1) \text{ div } 2 + m * t * (t - 1) \text{ div } 2 + m * u * (u - 1) \text{ div } 2 + m * v * (v - 1) \text{ div } 2 + s + t + u + v$ by fastforce*
hence *$N\text{-expr3: } N = m * s * (s - 1) \text{ div } 2 + s + m * t * (t - 1) \text{ div } 2 + t + m * u * (u - 1) \text{ div } 2 + u + m * v * (v - 1) \text{ div } 2 + v$ by auto*
define *sn::nat where sn = nat s*
define *tn::nat where tn = nat t*
define *un::nat where un = nat u*
define *vn::nat where vn = nat v*
have *sn = s using stuv sn-def by auto*
hence *$m * sn * (sn - 1) = m * s * (s - 1)$ by fastforce*

hence $m * sn * (sn-1) \text{ div } 2 = m * s * (s-1) \text{ div } 2$ **by** *linarith*
have $tn = t$ **using** *stuv tn-def* **by** *auto*
hence $m * tn * (tn-1) = m * t * (t-1)$ **by** *fastforce*
hence $m * tn * (tn-1) \text{ div } 2 = m * t * (t-1) \text{ div } 2$ **by** *linarith*
have $un = u$ **using** *stuv un-def* **by** *auto*
hence $m * un * (un-1) = m * u * (u-1)$ **by** *fastforce*
hence $m * un * (un-1) \text{ div } 2 = m * u * (u-1) \text{ div } 2$ **by** *linarith*
have $vn = v$ **using** *stuv vn-def* **by** *auto*
hence $m * vn * (vn-1) = m * v * (v-1)$ **by** *fastforce*
hence $m * vn * (vn-1) \text{ div } 2 = m * v * (v-1) \text{ div } 2$ **by** *linarith*
have $N = m * sn * (sn-1) \text{ div } 2 + sn + m * tn * (tn-1) \text{ div } 2 + tn + m * un * (un-1) \text{ div } 2 + un + m * vn * (vn-1) \text{ div } 2 + vn$
using *N-expr3* $\langle sn = s \rangle \langle tn = t \rangle \langle un = u \rangle \langle vn = v \rangle \langle m * sn * (sn-1) \text{ div } 2 = m * s * (s-1) \text{ div } 2 \rangle \langle m * tn * (tn-1) \text{ div } 2 = m * t * (t-1) \text{ div } 2 \rangle \langle m * un * (un-1) \text{ div } 2 = m * u * (u-1) \text{ div } 2 \rangle \langle m * vn * (vn-1) \text{ div } 2 = m * v * (v-1) \text{ div } 2 \rangle$ **by** *linarith*
hence $N = \text{polygonal-number } m \text{ sn} + \text{polygonal-number } m \text{ tn} + \text{polygonal-number } m \text{ un} + \text{polygonal-number } m \text{ vn}$
using *Polygonal-Number-Theorem-Gauss.polygonal-number-def* **by** *presburger*
thus *?thesis* **by** *blast*
qed

We show Legendre's polygonal number theorem which corresponds to Theorem 1.10 in [2].

theorem *Legendre-Polygonal-Number-Theorem*:

fixes $m \ N :: \text{nat}$
assumes $m \geq 3$
assumes $N \geq 28 * m^3$
shows $\text{odd } m \implies \exists k1 \ k2 \ k3 \ k4 :: \text{nat}. N = \text{polygonal-number } m \ k1 + \text{polygonal-number } m \ k2 + \text{polygonal-number } m \ k3 + \text{polygonal-number } m \ k4$
and $\text{even } m \implies \exists k1 \ k2 \ k3 \ k4 \ k5 :: \text{nat}. N = \text{polygonal-number } m \ k1 + \text{polygonal-number } m \ k2 + \text{polygonal-number } m \ k3 + \text{polygonal-number } m \ k4 + \text{polygonal-number } m \ k5 \wedge (k1 = 0 \vee k1 = 1 \vee k2 = 0 \vee k2 = 1 \vee k3 = 0 \vee k3 = 1 \vee k4 = 0 \vee k4 = 1 \vee k5 = 0 \vee k5 = 1)$

proof –

define $L :: \text{real}$ **where** $L = (2/3 + \text{sqrt } (8 * N / m - 8)) - (1/2 + \text{sqrt } (6 * N / m - 3))$
define I **where** $I = \{1/2 + \text{sqrt } (6 * N / m - 3) .. 2/3 + \text{sqrt } (8 * N / m - 8)\}$
from *assms(1)* **have** $m^3 \geq m$
by (*simp add: power3-eq-cube*)
hence $N \geq 2 * m$ **using** *assms* **by** *simp*
have $m\text{-pos}: m > 0$ **using** *assms(1)* **by** *simp*
have $L > 2 * \text{of-nat } m$ **using** *assms* $\langle N \geq 2 * m \rangle$ $m\text{-pos}$ $L\text{-def}$
apply –
apply (*rule interval-length-greater-than-2m* [**where** $N = \text{of-nat } N$ **and** $m = \text{of-nat } m$])
apply (*simp-all*)
by (*metis* (*no-types*, *opaque-lifting*) *of-nat-le-iff of-nat-mult of-nat-numeral*)

```

power3-eq-cube)
  hence 2:  $L > 2 * m$  by simp
  show thm-odd-m:  $odd\ m \implies \exists k1\ k2\ k3\ k4. N = polygonal-number\ m\ k1 +$ 
   $polygonal-number\ m\ k2 + polygonal-number\ m\ k3 + polygonal-number\ m\ k4$ 
  proof -
    assume odd-m:  $odd\ m$ 
    from assms(1) have  $m > 0$  by auto
    define ce where  $ce = \lceil 1/2 + \sqrt{6*N/m - 3} \rceil$ 
    have  $\forall i \in \{0..2*m-1\}. ce + i \geq ce$  by auto
    hence lower-bound:  $\forall i \in \{0..2*m-1\}. ce + i \geq 1/2 + \sqrt{6*N/m - 3}$ 
  using ceiling-le-iff ce-def by blast
    have  $2*m-1 + ce \leq 2/3 + \sqrt{8*N/m - 8}$  using 2 L-def assms(1) ce-def
  by linarith
    hence upper-bound:  $\forall i \in \{0..2*m-1\}. ce + i \leq 2/3 + \sqrt{8*N/m - 8}$ 
  by auto
    from lower-bound upper-bound have in-interval:  $\forall i \in \{0..2*m-1\}. ce + i \in I$ 
  unfolding ce-def I-def by auto
    have  $\exists f::nat \Rightarrow int. (\forall i \in \{0..m-1\}. odd\ (f\ i)) \wedge (\forall i \in \{1..m-1\}. f\ i = f\ 0$ 
   $+ 2*i) \wedge (\forall i \in \{0..m-1\}. f\ i \in I)$ 
    proof -
      have ?thesis if odd-f0:  $odd\ ce$ 
      proof -
        define  $g::nat \Rightarrow int$  where  $g\ i = ce + 2*i$ 
        have  $odd\ (g\ 0)$  using odd-f0  $\langle g \equiv \lambda i. ce + int\ (2 * i) \rangle$  by auto
        hence  $\forall i \in \{0..m-1\}. odd\ (g\ i)$  using  $\langle g \equiv \lambda i. ce + int\ (2 * i) \rangle$  by auto
        have  $\forall i \in \{1..m-1\}. g\ i = g\ 0 + 2*i$  using  $\langle g \equiv \lambda i. ce + int\ (2 * i) \rangle$  by
      auto
        have  $\forall i \in \{0..m-1\}. 2*i < 2*m-1$  using m-pos by auto
        hence  $\forall i \in \{0..m-1\}. g\ i \in I$  using  $\langle g \equiv \lambda i. ce + int\ (2 * i) \rangle$  in-interval
      by fastforce
        show ?thesis using  $\langle \forall i \in \{0..m-1\}. odd\ (g\ i) \rangle \langle \forall i \in \{0..m-1\}. real-of-int$ 
       $(g\ i) \in I \rangle \langle \forall i \in \{1..m-1\}. g\ i = g\ 0 + int\ (2 * i) \rangle$  by blast
        qed
      moreover have ?thesis if even ce
      proof -
        from  $\langle even\ ce \rangle$  have odd-f1:  $odd\ (ce + 1)$  by auto
        define  $g::nat \Rightarrow int$  where  $g\ i = ce + (2*i + 1)$ 
        have  $odd\ (g\ 0)$  using odd-f1  $\langle g \equiv \lambda i. ce + int\ (2 * i + 1) \rangle$  by auto
        hence  $\forall i \in \{0..m-1\}. odd\ (g\ i)$  using  $\langle g \equiv \lambda i. ce + int\ (2 * i + 1) \rangle$  by
      auto
        have  $\forall i \in \{1..m-1\}. g\ i = g\ 0 + 2*i$  using  $\langle g \equiv \lambda i. ce + int\ (2 * i +$ 
       $1) \rangle$  by auto
        have  $\forall i \in \{0..m-1\}. 2*i + 1 \leq 2*m-1$  using m-pos by auto
        hence  $\forall i \in \{0..m-1\}. g\ i \in I$  using  $\langle g \equiv \lambda i. ce + int\ (2 * i + 1) \rangle$ 
      in-interval by fastforce
        show ?thesis using  $\langle \forall i \in \{0..m-1\}. odd\ (g\ i) \rangle \langle \forall i \in \{0..m-1\}. real-of-int$ 
       $(g\ i) \in I \rangle \langle \forall i \in \{1..m-1\}. g\ i = g\ 0 + int\ (2 * i) \rangle$  by blast
        qed
      ultimately show ?thesis by blast

```

qed
then obtain $f::nat \Rightarrow int$ **where** $f\text{-def}: (\forall i \in \{0..m-1\}. odd (f i)) \wedge (\forall i \in \{1..m-1\}. f i = f 0 + 2*i) \wedge (\forall i \in \{0..m-1\}. f i \in I)$ **by auto**

have $inj\text{-lemma}: \llbracket i \in \{0..m-1\}; j \in \{0..m-1\}; [f i = f j] (mod m) \rrbracket \Longrightarrow i = j$ **for** $i j$

proof –

assume $asm1: i \in \{0..m-1\}$
assume $asm2: j \in \{0..m-1\}$
assume $asm3: [f i = f j] (mod m)$
from $f\text{-def}$ **have** $odd (f 0)$ **by auto**
hence $\exists k::int. f 0 = 2*k + 1$ **by** ($metis oddE$)
then obtain $k::int$ **where** $k\text{-def}: f 0 = 2*k + 1$ **by auto**
have $False$ **if** $case2: i = 0 \wedge j > 0$

proof –

have $f j = f 0 + 2*j$ **using** $f\text{-def}$ $case2$ $asm2$ **by auto**
hence $[2*k + 1 = 2*k + 1 + 2*j] (mod m)$ **using** $asm3$ $case2$ $k\text{-def}$ **by**

$auto$

hence $[2*j = 0] (mod m)$
by ($metis cong-add-lcancel-0 cong-int-iff cong-sym-eq int-ops(1)$)
have $coprime 2 m$ **using** $odd\text{-}m$ **by simp**
hence $[j = 0] (mod m)$ **using** $\langle [2*j = 0] (mod m) \rangle$ **by** ($simp add: cong-0-iff coprime-dvd-mult-right-iff$)
thus $False$ **using** $asm2$ $case2$ $cong\text{-less-modulus-unique-nat}$ **by fastforce**

qed

moreover **have** $False$ **if** $case3: i > 0 \wedge j = 0$

proof –

have $f i = f 0 + 2*i$ **using** $f\text{-def}$ $case3$ $asm1$ **by auto**
hence $[2*k + 1 + 2*i = 2*k + 1] (mod m)$ **using** $asm3$ $case3$ $k\text{-def}$ **by**

$auto$

hence $[2*i = 0] (mod m)$
by ($metis cong-add-lcancel-0 cong-int-iff cong-sym-eq int-ops(1)$)
have $coprime 2 m$ **using** $odd\text{-}m$ **by simp**
hence $[i = 0] (mod m)$ **using** $\langle [2*i = 0] (mod m) \rangle$ **by** ($simp add: cong-0-iff coprime-dvd-mult-right-iff$)
thus $False$ **using** $asm1$ $case3$ $cong\text{-less-modulus-unique-nat}$ **by fastforce**

qed

moreover **have** $?thesis$ **if** $case4: i > 0 \wedge j > 0$

proof –

have $i > 0$ **and** $j > 0$ **using** $case4$ **by auto**
have $f i = f 0 + 2*i$ **using** $f\text{-def}$ $case4$ $asm1$ **by auto**
moreover **have** $f j = f 0 + 2*j$ **using** $f\text{-def}$ $case4$ $asm2$ **by auto**
ultimately **have** $[2*k + 1 + 2*i = 2*k + 1 + 2*j] (mod m)$ **using** $case4$

$k\text{-def}$ $asm3$ **by fastforce**

hence $[2*i = 2*j] (mod m)$
using $cong\text{-add-lcancel}$ $cong\text{-int-iff}$ **by blast**
have $coprime 2 m$ **using** $odd\text{-}m$ **by simp**
hence $[i = j] (mod m)$
using $\langle [2 * i = 2 * j] (mod m) \rangle$ $cong\text{-mult-lcancel-nat}$ **by auto**

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    thus ?thesis using asm1 asm2 case4 cong-less-modulus-unique-nat by auto
  qed
  ultimately show ?thesis by fastforce
  qed
  have complete-cong-class:  $\exists i \in \{0..m-1\}. [f i = S] \pmod m$  for  $S$ 
  proof -
    have  $(f i) \pmod m = (f j) \pmod m \implies [f i = f j] \pmod m$  for  $i j$ 
      by (simp add: unique-euclidean-semiring-class.cong-def)
    hence inj2:  $[[i \in \{0..m-1\}; j \in \{0..m-1\}; (f i) \pmod m = (f j) \pmod m]] \implies$ 
 $i = j$  for  $i j$ 
      using inj-lemma by auto
    hence injective:  $\forall i \in \{0..m-1\}. \forall j \in \{0..m-1\}. (f i) \pmod m = (f j) \pmod$ 
 $m \longrightarrow i = j$ 
      by auto
    define  $g :: nat \Rightarrow int$  where  $g i = (f i) \pmod m$ 
    then have  $g$ -inj2:  $\forall i \in \{0..m-1\}. \forall j \in \{0..m-1\}. g i = g j \longrightarrow i = j$ 
      using  $\langle g \equiv \lambda i. f i \pmod{int m} \rangle$  injective by fastforce
    then have  $g$ -inj:  $inj\text{-on } g \{0..m-1\}$ 
      by (meson inj-onI)
    have  $g$ -range2:  $\forall i \in \{0..m-1\}. g i \in \{0..m-1\}$  using  $\langle g \equiv \lambda i. f i \pmod{int}$ 
 $m \rangle$ 
      by (metis  $m$ -pos Euclidean-Rings.pos-mod-bound Euclidean-Rings.pos-mod-sign
atLeastAtMost-iff mod-by-1 mod-if-not-gr0 of-nat-0-less-iff of-nat-1 of-nat-diff verit-comp-simplify1(3)
zle-diff1-eq)
    hence image-subset:  $g \text{ ' } \{0..m-1\} \subseteq \{0..m-1\}$  by blast
    have  $g$ -range:  $i \in \{0..m-1\} \implies g i \in \{0..m-1\}$  using  $\langle g \equiv \lambda i. f i \pmod{int}$ 
 $m \rangle$ 
      by (metis  $m$ -pos Euclidean-Rings.pos-mod-bound Euclidean-Rings.pos-mod-sign
atLeastAtMost-iff mod-by-1 mod-if-not-gr0 of-nat-0-less-iff of-nat-1 of-nat-diff verit-comp-simplify1(3)
zle-diff1-eq)
    have card-ge-m:  $card (g \text{ ' } \{0..m-1\}) \geq m$  using  $g$ -inj
      by (metis  $m$ -pos Suc-diff-1 card-atLeastAtMost card-image minus-nat.diff-0
verit-comp-simplify1(2))
    have card  $\{0..m-1\} = m$  using  $m$ -pos by force
    hence card-le-m:  $card (g \text{ ' } \{0..m-1\}) \leq m$  using  $m$ -pos
      by (metis card-image  $g$ -inj le-refl)
    from card-ge-m card-le-m have image-size:  $card (g \text{ ' } \{0..m-1\}) = m$  by auto
    with  $\langle card \{0..m-1\} = m \rangle$  have equal-card:  $card (g \text{ ' } \{0..m-1\}) = card$ 
 $\{0..m-1\}$  by auto
    have finite  $(g \text{ ' } \{0..m-1\})$  using image-size by auto
    with equal-card image-subset have  $g \text{ ' } \{0..m-1\} = \{0..m-1\}$ 
    by (metis card-image card-subset-eq finite-atLeastAtMost-int image-int-atLeastAtMost
inj-on-of-nat of-nat-0)
    hence  $i \in \{0..m-1\} \implies \exists j \in \{0..m-1\}. i = g j$  for  $i$  by auto
    hence  $i \in \{0..m-1\} \implies \exists j \in \{0..m-1\}. i = (f j) \pmod m$  for  $i$ 
      using  $\langle g \equiv \lambda i. f i \pmod{int m} \rangle$  by auto
    hence surj:  $i \in \{0..m-1\} \implies \exists j \in \{0..m-1\}. [i = f j] \pmod m$  for  $i$ 
      by (metis mod-mod-trivial unique-euclidean-semiring-class.cong-def)
    have  $S \pmod m \geq 0$  using  $m$ -pos by simp

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moreover have  $S \bmod m \leq m-1$ 
  using  $m\text{-pos}$  by (simp add: of-nat-diff)
ultimately have  $S \bmod m \in \{0..m-1\}$  by auto
with  $\text{surj } m\text{-pos}$  have  $\exists j \in \{0..m-1\}. [S \bmod m = f j] \pmod m$ 
by (metis atLeastAtMost-iff less-eq-nat.simps(1) nonneg-int-cases of-nat-less-iff
verit-comp-simplify(3))
  thus ?thesis using cong-mod-right cong-sym by blast
qed
have  $\exists b::\text{int}. [N = b] \pmod m \wedge \text{odd } b \wedge b \in I$ 
proof –
  have  $N \bmod m \geq 0$  by auto
  moreover have  $N \bmod m \leq m-1$ 
    using  $m\text{-pos}$  less-Suc-eq-le by fastforce
  ultimately have  $N \bmod m \in \{0..m-1\}$  by auto
  with complete-cong-class have  $\exists i. i \in \{0..m-1\} \wedge [f i = N] \pmod m$  by
blast
  then obtain  $c::\text{nat}$  where  $c\text{-def}: c \in \{0..m-1\} \wedge [f c = N] \pmod m$  by
auto
  define  $b::\text{int}$  where  $b = f c$ 
  have  $[N = b] \pmod m$  using  $b\text{-def } c\text{-def}$  by (metis cong-sym)
  moreover have  $\text{odd } b$  using  $b\text{-def } f\text{-def } c\text{-def}$  by auto
  moreover have  $b \in I$  using  $b\text{-def } f\text{-def } c\text{-def}$  by auto
  ultimately show ?thesis by auto
qed
then obtain  $b::\text{int}$  where  $b\text{-def}: [N = b] \pmod m \wedge \text{odd } b \wedge b \in I$  by auto
have  $m^{\wedge}3 \geq m$  using  $m\text{-pos}$  by (auto simp add: power3-eq-cube)
hence  $N \geq 28*m$  using  $\text{assms}(1,2)$  by linarith
hence  $N \geq 2*m$  by simp
have  $m^{\wedge}3 \geq 3*3*(3::\text{nat})$  using  $\text{assms}(1)$ 
  by (metis power3-eq-cube power-mono zero-le-numeral)
hence  $N \geq 28*3*3*(3::\text{nat})$  using  $\text{assms}(2)$  by auto
hence  $N \geq 9$  by simp
show ?thesis using sum-of-four-polygonal-numbers assms(1) b-def I-def  $\langle N \geq$ 
 $2 * m \rangle \langle N \geq 9 \rangle$  by blast
qed
show thm-even-m: even m  $\implies \exists k1 k2 k3 k4 k5. N = \text{polygonal-number } m k1$ 
 $+ \text{polygonal-number } m k2 + \text{polygonal-number } m k3 + \text{polygonal-number } m k4 +$ 
 $\text{polygonal-number } m k5 \wedge (k1 = 0 \vee k1 = 1 \vee k2 = 0 \vee k2 = 1 \vee k3 = 0 \vee k3 = 1$ 
 $\vee k4 = 0 \vee k4 = 1 \vee k5 = 0 \vee k5 = 1)$ 
proof –
  assume even-m: even m
  from  $\text{assms}(1)$  have  $m > 0$  by auto
  define  $ce$  where  $ce = \lceil 1/2 + \text{sqrt } (6*N/m - 3) \rceil$ 
  have  $\forall i \in \{0..m-1\}. ce + i \geq ce$  by auto
  hence lower-bound:  $\forall i \in \{0..m-1\}. ce + i \geq 1/2 + \text{sqrt } (6*N/m - 3)$  using
ceiling-le-iff ce-def by blast
  have  $m-1 + ce \leq 2/3 + \text{sqrt } (8*N/m - 8)$  using  $2$  L-def assms(1) ce-def
by linarith
  hence upper-bound:  $\forall i \in \{0..m-1\}. ce + i \leq 2/3 + \text{sqrt } (8*N/m - 8)$  by

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auto
  from lower-bound upper-bound have in-interval:  $\forall i \in \{0..m-1\}. ce + i \in I$ 
  unfolding ce-def I-def by auto
  have  $\exists f::nat \Rightarrow int. (\forall i \in \{1..m-1\}. f i = f 0 + i) \wedge (\forall i \in \{0..m-1\}. f i \in I)$ 
  proof -
    define  $g::nat \Rightarrow int$  where  $g i = ce + i$ 
    have  $\forall i \in \{1..m-1\}. g i = g 0 + i$  using  $\langle g \equiv \lambda i. ce + int i \rangle$  by auto
    have  $\forall i \in \{0..m-1\}. i < m$  using m-pos by auto
    hence  $\forall i \in \{0..m-1\}. g i \in I$  using  $\langle g \equiv \lambda i. ce + int i \rangle$  in-interval by
  fastforce
    show ?thesis by (metis Num.of-nat-simps(1)  $\langle \forall i \in \{0..m-1\}. real-of-int (g i) \in I \rangle \langle g \equiv \lambda i. ce + int i \rangle$  arith-extra-simps(6))
  qed
  then obtain  $f::nat \Rightarrow int$  where f-def:  $(\forall i \in \{1..m-1\}. f i = f 0 + i) \wedge (\forall i \in \{0..m-1\}. f i \in I)$  by auto
  have inj-lemma:  $\llbracket i \in \{0..m-1\}; j \in \{0..m-1\}; [f i = f j] \pmod m \rrbracket \Longrightarrow i = j$ 
  for  $i j$ 
  proof -
    assume asm1:  $i \in \{0..m-1\}$ 
    assume asm2:  $j \in \{0..m-1\}$ 
    assume asm3:  $[f i = f j] \pmod m$ 
    have False if case2:  $i = 0 \wedge j > 0$ 
    proof -
      have  $f j = f 0 + j$  using f-def case2 asm2 by auto
      hence  $[f 0 = f 0 + j] \pmod m$  using asm3 case2 by auto
      hence  $[j = 0] \pmod m$ 
      by (metis cong-add-lcancel-0 cong-int-iff cong-sym-eq int-ops(1))
      thus False using asm2 case2 cong-less-modulus-unique-nat by fastforce
    qed
    moreover have False if case3:  $i > 0 \wedge j = 0$ 
    proof -
      have  $f i = f 0 + i$  using f-def case3 asm1 by auto
      hence  $[f 0 + i = f 0] \pmod m$  using asm3 case3 by auto
      hence  $[i = 0] \pmod m$ 
      by (metis cong-add-lcancel-0 cong-int-iff cong-sym-eq int-ops(1))
      thus False using asm1 case3 cong-less-modulus-unique-nat by fastforce
    qed
    moreover have ?thesis if case4:  $i > 0 \wedge j > 0$ 
    proof -
      have  $i > 0$  and  $j > 0$  using case4 by auto
      have  $f i = f 0 + i$  using f-def case4 asm1 by auto
      moreover have  $f j = f 0 + j$  using f-def case4 asm2 by auto
      ultimately have  $[f 0 + i = f 0 + j] \pmod m$  using case4 asm3 by fastforce
      hence  $[i = j] \pmod m$ 
      using cong-add-lcancel cong-int-iff by blast
      thus ?thesis using asm1 asm2 case4 cong-less-modulus-unique-nat by auto
    qed
  ultimately show ?thesis by fastforce

```



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qed
have complete-cong-class:  $\exists i \in \{0..m-1\}. [f i = S] \pmod m$  for  $S$ 
proof -
  have  $(f i) \pmod m = (f j) \pmod m \implies [f i = f j] \pmod m$  for  $i j$ 
    by (simp add: unique-euclidean-semiring-class.cong-def)
  hence inj2:  $[[i \in \{0..m-1\}; j \in \{0..m-1\}; (f i) \pmod m = (f j) \pmod m]] \implies$ 
 $i = j$  for  $i j$ 
    using inj-lemma by auto
  hence injective:  $\forall i \in \{0..m-1\}. \forall j \in \{0..m-1\}. (f i) \pmod m = (f j) \pmod$ 
 $m \implies i = j$ 
    by auto
  define  $g :: nat \Rightarrow int$  where  $g i = (f i) \pmod m$ 
  then have  $g\text{-inj2}: \forall i \in \{0..m-1\}. \forall j \in \{0..m-1\}. g i = g j \implies i = j$ 
    using  $\langle g \equiv \lambda i. f i \pmod{int m} \rangle$  injective by fastforce
  then have  $g\text{-inj}: inj\text{-on } g \{0..m-1\}$ 
    by (meson inj-onI)
  have  $g\text{-range2}: \forall i \in \{0..m-1\}. g i \in \{0..m-1\}$  using  $\langle g \equiv \lambda i. f i \pmod{int}$ 
 $m \rangle$ 
    by (metis  $m\text{-pos Euclidean-Rings.pos-mod-bound Euclidean-Rings.pos-mod-sign}$ 
 $atLeastAtMost\text{-iff mod-by-1 mod-if not-gr0 of-nat-0-less-iff of-nat-1 of-nat-diff verit-comp-simplify1 (3)$ 
 $zle-diff1\text{-eq}$ )
  hence image-subset:  $g \text{ ' } \{0..m-1\} \subseteq \{0..m-1\}$  by blast
  have  $g\text{-range}: i \in \{0..m-1\} \implies g i \in \{0..m-1\}$  using  $\langle g \equiv \lambda i. f i \pmod{int}$ 
 $m \rangle$ 
    by (metis  $m\text{-pos Euclidean-Rings.pos-mod-bound Euclidean-Rings.pos-mod-sign}$ 
 $atLeastAtMost\text{-iff mod-by-1 mod-if not-gr0 of-nat-0-less-iff of-nat-1 of-nat-diff verit-comp-simplify1 (3)$ 
 $zle-diff1\text{-eq}$ )
  have  $card\text{-ge-}m: card (g \text{ ' } \{0..m-1\}) \geq m$  using  $g\text{-inj}$ 
    by (metis  $m\text{-pos Suc-diff-1 card-atLeastAtMost card-image minus-nat.diff-0}$ 
 $verit-comp-simplify1 (2))$ 
  have  $card \{0..m-1\} = m$  using  $m\text{-pos}$  by force
  hence  $card\text{-le-}m: card (g \text{ ' } \{0..m-1\}) \leq m$  using  $m\text{-pos}$ 
    by (metis  $card\text{-image } g\text{-inj le-refl}$ )
  from  $card\text{-ge-}m$   $card\text{-le-}m$  have  $image\text{-size}: card (g \text{ ' } \{0..m-1\}) = m$  by auto
  with  $\langle card \{0..m-1\} = m \rangle$  have  $equal\text{-card}: card (g \text{ ' } \{0..m-1\}) = card$ 
 $\{0..m-1\}$  by auto
  have  $finite (g \text{ ' } \{0..m-1\})$  using  $image\text{-size}$  by auto
  with  $equal\text{-card image-subset}$  have  $g \text{ ' } \{0..m-1\} = \{0..m-1\}$ 
  by (metis  $card\text{-image card-subset-eq finite-atLeastAtMost-int image-int-atLeastAtMost}$ 
 $inj\text{-on-of-nat of-nat-0}$ )
  hence  $i \in \{0..m-1\} \implies \exists j \in \{0..m-1\}. i = g j$  for  $i$  by auto
  hence  $i \in \{0..m-1\} \implies \exists j \in \{0..m-1\}. i = (f j) \pmod m$  for  $i$ 
    using  $\langle g \equiv \lambda i. f i \pmod{int m} \rangle$  by auto
  hence  $surj: i \in \{0..m-1\} \implies \exists j \in \{0..m-1\}. [i = f j] \pmod m$  for  $i$ 
    by (metis  $mod\text{-mod-trivial unique-euclidean-semiring-class.cong-def}$ )
  have  $S \pmod m \geq 0$  using  $m\text{-pos}$  by simp
  moreover have  $S \pmod m \leq m-1$ 
    using  $m\text{-pos}$  by (simp add:  $of\text{-nat-diff}$ )
  ultimately have  $S \pmod m \in \{0..m-1\}$  by auto

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with surj m-pos have  $\exists j \in \{0..m-1\}. [S \bmod m = f j] \pmod m$ 
by (metis atLeastAtMost-iff less-eq-nat.simps(1) nonneg-int-cases of-nat-less-iff
verit-comp-simplify(3))
thus ?thesis using cong-mod-right cong-sym by blast
qed
have thm-odd-n: ?thesis if odd N
proof –
have  $\exists b::int. [N = b] \pmod m \wedge \text{odd } b \wedge b \in I$ 
proof –
from complete-cong-class have  $\exists i. i \in \{0..m-1\} \wedge [f i = N] \pmod m$  by
blast
then obtain c::nat where c-def: c  $\in \{0..m-1\} \wedge [f c = N] \pmod m$  by
auto
define b::int where  $b = f c$ 
have  $[N = b] \pmod m$  using b-def c-def by (metis cong-sym)
moreover have odd b
proof
assume even b
have  $\exists k::int. N = b + k*m$  using  $\langle [N = b] \pmod m \rangle$ 
by (metis cong-iff-lin cong-sym-eq mult.commute)
then obtain k::int where k-def: N  $= b + k*m$  by auto
have even (k*m) using even-m by auto
hence even N using k-def  $\langle \text{even } b \rangle$  by presburger
thus False using  $\langle \text{odd } N \rangle$  by blast
qed
moreover have  $b \in I$  using b-def f-def c-def by auto
ultimately show ?thesis by auto
qed
then obtain b::int where b-def: [N = b] mod m  $\wedge \text{odd } b \wedge b \in I$  by auto
have  $m^{\wedge}3 \geq m$  using m-pos by (auto simp add: power3-eq-cube)
hence  $N \geq 28*m$  using assms(1,2) by linarith
hence  $N \geq 2*m$  by simp
have  $m^{\wedge}3 \geq 3*3*(3::nat)$  using assms(1)
by (metis power3-eq-cube power-mono zero-le-numeral)
hence  $N \geq 28*3*3*(3::nat)$  using assms(2) by auto
hence  $N \geq 9$  by simp
hence  $\exists k1\ k2\ k3\ k4. N = \text{polygonal-number } m\ k1 + \text{polygonal-number } m\ k2$ 
 $+ \text{polygonal-number } m\ k3 + \text{polygonal-number } m\ k4$ 
using sum-of-four-polygonal-numbers assms(1) b-def I-def  $\langle N \geq 2 * m \rangle \langle N$ 
 $\geq 9 \rangle$  by blast
then obtain k1 k2 k3 k4 where  $N = \text{polygonal-number } m\ k1 + \text{polygo}$ 
 $\text{-nal-number } m\ k2 + \text{polygonal-number } m\ k3 + \text{polygonal-number } m\ k4$  by blast
moreover have polygonal-number m 0 = 0 using Polygonal-Number-Theorem-Gauss.polygonal-number-de
by auto
ultimately have  $N = \text{polygonal-number } m\ k1 + \text{polygonal-number } m\ k2$ 
 $+ \text{polygonal-number } m\ k3 + \text{polygonal-number } m\ k4 + \text{polygonal-number } m\ 0$  by
linarith
thus ?thesis by blast
qed

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have thm-even-n: ?thesis if even N
proof -
  have  $\exists b::int. [N-1 = b] \pmod m \wedge \text{odd } b \wedge b \in I$ 
  proof -
    from complete-cong-class have  $\exists i. i \in \{0..m-1\} \wedge [f i = N-1] \pmod m$ 
  by blast
  then obtain  $c::nat$  where  $c\text{-def}: c \in \{0..m-1\} \wedge [f c = N-1] \pmod m$ 
  by auto
  define  $b::int$  where  $b = f c$ 
  have  $[N-1 = b] \pmod m$  using  $b\text{-def } c\text{-def}$  by (metis cong-sym)
  moreover have odd b
  proof
    assume even b
    have  $\exists k::int. N-1 = b + k*m$  using  $\langle [N-1 = b] \pmod m \rangle$ 
    by (metis (full-types) cong-iff-lin cong-sym-eq mult.commute)
    then obtain  $k::int$  where  $k\text{-def}: N-1 = b + k*m$  by auto
    have even (k*m) using even-m by auto
    hence even (N-1) using  $k\text{-def} \langle \text{even } b \rangle$  by presburger
    hence odd N
    by (metis Groups.mult-ac(2)  $\langle 2 * m \leq N \rangle$  add-eq-self-zero add-leD1
    assms(1) dvd-diffD1 le-trans mult-2-right nat-1-add-1 nat-dvd-1-iff-1 rel-simps(25)
    zero-neq-numeral)
  thus False using  $\langle \text{even } N \rangle$  by blast
  qed
  moreover have  $b \in I$  using  $b\text{-def } f\text{-def } c\text{-def}$  by auto
  ultimately show ?thesis by auto
qed
then obtain  $b::int$  where  $b\text{-def}: [N-1 = b] \pmod m \wedge \text{odd } b \wedge b \in I$  by
auto
from  $b\text{-def}$  have  $b \in I$  by auto
define  $a::int$  where  $a\text{-def}: a = 2*(N-1-b) \text{ div } m + b$ 
have  $m \text{ dvd } (N-1-b)$  using  $b\text{-def}$ 
  by (smt (verit, ccfv-threshold) cong-iff-dvd-diff zdvd-zdiffD)
hence even  $(2*(N-1-b) \text{ div } m)$ 
  by (metis div-mult-swap dvd-triv-left)
hence odd a using  $a\text{-def } b\text{-def}$  by auto
from assms(1) have  $m^3 \geq m$ 
  by (simp add: power3-eq-cube)
hence  $N \geq 2 * m$  using assms(1,2) by simp
from assms(1) have  $m\text{-pos}: m > 0$  by auto
have  $N-1 \geq b$ 
proof -
  from assms(1) have  $m \geq 1$  by auto
  hence  $1/m \leq 1$  using  $m\text{-pos}$  by auto
  moreover have  $N > 0$  using  $\langle N \geq 2 * m \rangle m\text{-pos}$  by auto
  ultimately have  $N/m \leq N$ 
    using divide-less-eq-1 less-eq-real-def by fastforce
  hence  $\text{sqrt}(8*N/m - 8) \leq \text{sqrt}(8*(N-1))$  by auto
  from assms(1) have  $m^3 \geq 3*3*(3::real)$ 

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by (metis numeral-le-real-of-nat-iff numeral-times-numeral power3-eq-cube
 power-mono zero-le-numeral)
 hence $N \geq 28 * 3 * 3 * (3 :: \text{real})$ using *assms(2)* by *linarith*
 hence $N - 6 \geq 6$ by *simp*
 hence $N - 6 \geq 0$ by *simp*
 with $\langle N - 6 \geq 6 \rangle$ have $(N - 6)^2 \geq 6^2$
 using *power2-nat-le-eq-le* by *blast*
 hence $(N - 6)^2 \geq 24$ by *simp*
 hence $(N - 2)^2 \geq 8 * (N - 1)$ by (simp add: *power2-eq-square algebra-simps*)
 hence $(N - 2) \geq \text{sqrt}(8 * (N - 1))$ using $\langle N > 0 \rangle$
 by (metis *of-nat-0-le-iff of-nat-mono of-nat-power real-sqrt-le-mono*
real-sqrt-pow2 real-sqrt-power)
 hence $N - (2 :: \text{real}) - \text{sqrt}(8 * N / m - 8) \geq 0$
 using $\langle \text{sqrt}(\text{real}(8 * N) / \text{real } m - 8) \leq \text{sqrt}(\text{real}(8 * (N - 1))) \rangle$
 $\langle N - 6 \geq 6 \rangle$ by *linarith*
 hence *expr-pos*: $N - 1 - (2/3 :: \text{real}) - \text{sqrt}(8 * N / m - 8) \geq 0$ by *auto*
 have $b \leq 2/3 + \text{sqrt}(8 * N / m - 8)$ using $\langle b \in I \rangle$ *I-def* by *auto*
 hence $N - 1 - b \geq N - 1 - (2/3 + \text{sqrt}(8 * N / m - 8))$ by *auto*
 hence $N - 1 - b \geq 0$
 using *expr-pos of-int-0-le-iff* by *auto*
 thus *?thesis* by *auto*
 qed
 from $\langle N \geq 2 * m \rangle$ *m-pos* have $6 * N / m - 3 \geq 0$ by (simp add: *mult-imp-le-div-pos*)
 hence $1/2 + \text{sqrt}(6 * N / m - 3) > 0$
 by (smt (*verit, del-insts*) *divide-le-0-1-iff real-sqrt-ge-zero*)
 with $\langle b \in I \rangle$ *b-def I-def* have $b \geq 1$ by *auto*
 hence *b-pos*: $b \geq 0$ by *auto*
 from $\langle b \in I \rangle$ have *b-in-I*: $(1/2 :: \text{real}) + \text{sqrt}(6 * \text{real } N / \text{real } m - 3) \leq b$
 $\wedge b \leq (2/3 :: \text{real}) + \text{sqrt}(8 * \text{real } N / \text{real } m - 8)$ *unfolding I-def* by *auto*
 from *b-pos* $\langle N - 1 \geq b \rangle$ *a-def* have *a-pos*: $a \geq 0$
 by (smt (*verit*) *m-pos of-nat-0-less-iff pos-imp-zdiv-neg-iff*)
 hence $a \geq 1$
 by (smt (*verit*) *odd a dvd-0-right*)
 have $a - b = 2 * (N - 1 - b) \text{ div } m$ using *a-def* by *auto*
 from $\langle \text{int } m \text{ dvd } (N - 1 - b) \rangle$ have $m \text{ dvd } 2 * (N - 1 - b)$ by *fastforce*
 have $a = 2 * (N - 1 - b) / m + b$ using *a-def m-pos*
 using $\langle \text{int } m \text{ dvd } 2 * (N - 1 - b) \rangle$ by *fastforce*
 hence $a = 2 * (N - 1) / m - 2 * b / m + b$
 by (simp add: *assms diff-divide-distrib of-nat-diff*)
 hence $(2 :: \text{real}) * (N - 1) / m = a + 2 * b / m - b$ by *auto*
 hence $(2 :: \text{real}) * (N - 1) = (a + 2 * b / m - b) * m$
 using *m-pos* by (simp add: *divide-eq-eq*)
 hence $(2 :: \text{real}) * (N - 1) = m * (a - b) + 2 * b$
 using $\langle \text{int } m \text{ dvd } 2 * (N - 1 - b) \rangle$ *a-def* by *auto*
 hence $N - 1 = m * (a - b) / 2 + b$ by *auto*
 hence $N = m * (a - b) / 2 + b + 1$
 using $\langle 2 * m \leq N \rangle$ *assms(1)* by *linarith*
 hence *N-expr*: $N = \text{real } m * (\text{of-int } a - \text{of-int } b) / 2 + \text{of-int } b + 1$ by *auto*
 have *even (a - b)* using *odd a b-def* by *auto*

hence $2 \text{ dvd } m*(a-b)$ **by** *auto*
hence $N\text{-expr2}: N = m*(a-b) \text{ div } 2 + b + 1$ **using** $\langle N = m*(a-b)/2 + b + 1 \rangle$ **by** *linarith*
define Nr **where** $Nr = \text{real-of-nat } N$
define mr **where** $mr = \text{real } m$
define ar **where** $ar = \text{real-of-int } a$
define br **where** $br = \text{real-of-int } b$
from *assms(1)* **have** $mr \geq 3$ **using** *mr-def* **by** *auto*
moreover **have** $Nr \geq 2*mr$ **using** *Nr-def mr-def* $\langle N \geq 2 * m \rangle$ **by** *auto*
moreover **have** $br \geq 0$ **using** *br-def b-pos* **by** *auto*
moreover **have** $mr > 0$ **using** *mr-def m-pos* **by** *auto*
moreover **have** $ar \geq 0$ **using** *ar-def* $\langle a \geq 0 \rangle$ **by** *auto*
moreover **have** $Nr = mr*(ar-br)/2 + br + 1$ **using** *Nr-def mr-def ar-def br-def N-expr* **by** *auto*
moreover **have** $1/2 + \text{sqrt } (6*Nr/mr-3) \leq br \wedge br \leq 2/3 + \text{sqrt } (8*Nr/mr-8)$ **using** *Nr-def mr-def br-def b-in-I* **by** *auto*
ultimately **have** $br^2 < 4*ar \wedge 3*ar < br^2+2*br+4$ **using** *Cauchy-lemma* **by** *auto*
hence *real-ineq*: $(\text{real-of-int } b)^2 < 4*(\text{real-of-int } a) \wedge 3*(\text{real-of-int } a) < (\text{real-of-int } b)^2 + 2*(\text{real-of-int } b) + 4$
using *br-def ar-def* **by** *auto*
hence *int-ineq1*: $b^2 < 4*a$ **using** *of-int-less-iff* **by** *fastforce*
from *real-ineq* **have** *int-ineq2*: $3*a < b^2+2*b+4$ **using** *of-int-less-iff* **by** *fastforce*

define $an:: \text{nat}$ **where** $an = \text{nat } a$
from *a-pos* **have** $an = a$ **unfolding** *an-def* **by** *auto*
define $bn:: \text{nat}$ **where** $bn = \text{nat } b$
from *b-pos* **have** $bn = b$ **unfolding** *bn-def* **by** *auto*
have $an \geq 1$ **using** $\langle \text{int } an = a \rangle \langle a \geq 1 \rangle$ **by** *auto*
moreover **have** $bn \geq 1$ **using** $\langle \text{int } bn = b \rangle \langle b \geq 1 \rangle$ **by** *auto*
moreover **have** *odd an* **using** $\langle \text{odd } a \rangle \langle \text{int } an = a \rangle$ **by** *auto*
moreover **have** *odd bn* **using** *b-def* $\langle \text{int } bn = b \rangle$ **by** *auto*
moreover **have** $bn^2 < 4 * an$ **using** *int-ineq1* $\langle \text{int } an = a \rangle \langle \text{int } bn = b \rangle$
using *of-nat-less-iff* **by** *fastforce*
moreover **have** $3 * an < bn^2 + 2 * bn + 4$ **using** *int-ineq2* $\langle \text{int } an = a \rangle \langle \text{int } bn = b \rangle$
using *of-nat-less-iff* **by** *fastforce*
ultimately **have** $\exists s t u v :: \text{int. } s \geq 0 \wedge t \geq 0 \wedge u \geq 0 \wedge v \geq 0 \wedge an = s^2 + t^2 + u^2 + v^2 \wedge$
 $bn = s+t+u+v$ **using** *four-nonneg-int-sum* **by** *auto*
hence $\exists s t u v :: \text{int. } s \geq 0 \wedge t \geq 0 \wedge u \geq 0 \wedge v \geq 0 \wedge a = s^2 + t^2 + u^2 + v^2 \wedge$
 $b = s+t+u+v$ **using** $\langle \text{int } an = a \rangle \langle \text{int } bn = b \rangle$ **by** *auto*
then obtain $s t u v :: \text{int where } stuv: s \geq 0 \wedge t \geq 0 \wedge u \geq 0 \wedge v \geq 0 \wedge a = s^2 + t^2 + u^2 + v^2 \wedge$
 $b = s+t+u+v$ **by** *auto*
hence $N = (m*(s^2+t^2+u^2+v^2-s-t-u-v) \text{ div } 2) + s+t+u+v + 1$
using *N-expr2* **by** (*smt (verit, ccfv-threshold)*)

hence $N = (m * (s^2 - s + t^2 - t + u^2 - u + v^2 - v) \text{ div } 2) + s + t + u + v + 1$
by (*smt (verit, ccfv-SIG)*)
hence $N = (m * (s * (s-1) + t * (t-1) + u * (u-1) + v * (v-1)) \text{ div } 2)$
 $+ s + t + u + v + 1$ **by** (*simp add: power2-eq-square algebra-simps*)
hence *previous-step*: $N = (m * s * (s-1) + m * t * (t-1) + m * u * (u-1)$
 $+ m * v * (v-1)) \text{ div } 2 + s + t + u + v + 1$ **by** (*simp add: algebra-simps*)
moreover **have** $2 \text{ dvd } m * s * (s-1)$ **by** *simp*
moreover **have** $2 \text{ dvd } m * t * (t-1)$ **by** *simp*
moreover **have** $2 \text{ dvd } m * u * (u-1)$ **by** *simp*
moreover **have** $2 \text{ dvd } m * v * (v-1)$ **by** *simp*
ultimately **have** $N = m * s * (s-1) \text{ div } 2 + m * t * (t-1) \text{ div } 2 + m * u$
 $* (u-1) \text{ div } 2 + m * v * (v-1) \text{ div } 2 + s + t + u + v + 1$ **by** *fastforce*
hence *N-expr3*: $N = m * s * (s-1) \text{ div } 2 + s + m * t * (t-1) \text{ div } 2 + t +$
 $m * u * (u-1) \text{ div } 2 + u + m * v * (v-1) \text{ div } 2 + v + 1$ **by** *auto*
define *sn::nat* **where** $sn = nat\ s$
define *tn::nat* **where** $tn = nat\ t$
define *un::nat* **where** $un = nat\ u$
define *vn::nat* **where** $vn = nat\ v$
have $sn = s$ **using** *stuv sn-def* **by** *auto*
hence $m * sn * (sn-1) = m * s * (s-1)$ **by** *fastforce*
hence $m * sn * (sn-1) \text{ div } 2 = m * s * (s-1) \text{ div } 2$ **by** *linarith*
have $tn = t$ **using** *stuv tn-def* **by** *auto*
hence $m * tn * (tn-1) = m * t * (t-1)$ **by** *fastforce*
hence $m * tn * (tn-1) \text{ div } 2 = m * t * (t-1) \text{ div } 2$ **by** *linarith*
have $un = u$ **using** *stuv un-def* **by** *auto*
hence $m * un * (un-1) = m * u * (u-1)$ **by** *fastforce*
hence $m * un * (un-1) \text{ div } 2 = m * u * (u-1) \text{ div } 2$ **by** *linarith*
have $vn = v$ **using** *stuv vn-def* **by** *auto*
hence $m * vn * (vn-1) = m * v * (v-1)$ **by** *fastforce*
hence $m * vn * (vn-1) \text{ div } 2 = m * v * (v-1) \text{ div } 2$ **by** *linarith*
have $N = m * sn * (sn-1) \text{ div } 2 + sn + m * tn * (tn-1) \text{ div } 2 + tn + m$
 $* un * (un-1) \text{ div } 2 + un + m * vn * (vn-1) \text{ div } 2 + vn + 1$
using *N-expr3* $\langle sn = s \rangle \langle tn = t \rangle \langle un = u \rangle \langle vn = v \rangle \langle m * sn * (sn-1) \text{ div}$
 $2 = m * s * (s-1) \text{ div } 2 \rangle \langle m * tn * (tn-1) \text{ div } 2 = m * t * (t-1) \text{ div } 2 \rangle \langle m *$
 $un * (un-1) \text{ div } 2 = m * u * (u-1) \text{ div } 2 \rangle \langle m * vn * (vn-1) \text{ div } 2 = m * v *$
 $(v-1) \text{ div } 2 \rangle$ **by** *linarith*
hence $N = \text{polygonal-number } m\ sn + \text{polygonal-number } m\ tn + \text{polygo}$
 $\text{nal-number } m\ un + \text{polygonal-number } m\ vn + 1$
using *Polygonal-Number-Theorem-Gauss.polygonal-number-def* **by** *presburger*
also **have** $\text{polygonal-number } m\ 1 = 1$ **using** *Polygonal-Number-Theorem-Gauss.polygonal-number-def*
by *auto*
ultimately **have** $N = \text{polygonal-number } m\ sn + \text{polygonal-number } m\ tn$
 $+ \text{polygonal-number } m\ un + \text{polygonal-number } m\ vn + \text{polygonal-number } m\ 1$ **by**
auto
thus *?thesis* **by** *blast*
qed
show *?thesis* **using** *thm-odd-n thm-even-n* **by** *blast*
qed
qed

end

References

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