Sums of two and four squares

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June 16, 2019

Abstract

This document gives the formal proofs of the following results about the sums of two and four squares:

1. Any prime number $p \equiv 1 \bmod 4$ can be written as the sum of two squares.
2. (Lagrange) Any natural number can be written as the sum of four squares.

The proofs are largely based on chapters II and III of the book by Weil [Wei83].

The results have been formalised before in the proof assistant HOL Light [Har]. A more complete study of the sum of two squares, including the first result, has been formalised in Coq [The04]. The results can also be found as numbers 20 and 19 on the list of 'top 100 mathematical theorems' [Wie].

This research is part of an M.Sc. thesis under supervision of Jaap Top and Wim H. Hesselink (RU Groningen). For more information see [Oos07].

Contents

theory *TwoSquares*
imports
HOL−Number-Theory.Number-Theory
begin

context

fixes *sum2sq-nat* :: *nat* ⇒ *nat* ⇒ *nat*
defines *sum2sq-nat a b* ≡ *a^2+b^2*

fixes *is-sum2sq-nat* :: *nat* ⇒ *bool*
defines *is-sum2sq-nat n* ≡ (∃ *a b*. *n* = *sum2sq-nat a b*)

begin

private lemma *best-division-abs*: (*n*::*int*) > *0* ⟹ ∃ *k*. *2* ∗ |*a* − *k*∗*n*| ≤ *n*
⟨*proof*⟩ **definition**
sum2sq-int :: *int* × *int* ⇒ *int* **where**
sum2sq-int = (λ(*a*,*b*). *a^2+b^2*)

private definition
is-sum2sq-int :: *int* ⇒ *bool* **where**
is-sum2sq-int n ⟷ (∃ *a b*. *n* = *sum2sq-int*(*a*,*b*))

private lemma *sum2sq-int-nat-eq*: *sum2sq-nat a b* = *sum2sq-int* (*a*, *b*)
⟨*proof*⟩ **lemma** *is-sum2sq-int-nat-eq*: *is-sum2sq-nat n* = *is-sum2sq-int* (*int n*)
⟨*proof*⟩ **lemma** *product-two-squares-aux*: *sum2sq-int*(*a*, *b*) ∗ *sum2sq-int*(*c*, *d*) = *sum2sq-int*(*a*∗*c* − *b*∗*d*, *a*∗*d* + *b*∗*c*)
⟨*proof*⟩ **lemma** *product-two-squares-int*: *is-sum2sq-int m* ⟹ *is-sum2sq-int n* ⟹ *is-sum2sq-int* (*m*∗*n*)
⟨*proof*⟩ **lemma** *product-two-squares-nat*: *is-sum2sq-nat m* ⟹ *is-sum2sq-nat n* ⟹ *is-sum2sq-nat* (*m*∗*n*)
⟨*proof*⟩ **lemma** *sots1-aux*:
assumes *prime* (*4*∗*k*+*3*)
assumes *odd* (*multiplicity* (*4*∗*k*+*3*) *n*)
shows ¬ *is-sum2sq-nat n*
⟨*proof*⟩ **lemma** *sots1*: **assumes** *is-sum2sq-nat n*
shows ⋀ *k*. *prime* (*4*∗*k*+*3*) ⟶ *even* (*multiplicity* (*4*∗*k*+*3*) *n*)
⟨*proof*⟩ **lemma** *aux-lemma*: **assumes** [(*a*::*nat*) = *b*] (*mod c*) *b* < *c*
shows ∃ *k*. *a* = *c*∗*k* + *b*
⟨*proof*⟩ **lemma** *Legendre-1mod4*: *prime* (*4*∗*k*+*1*::*nat*) ⟹ (*Legendre* (−*1*) (*4*∗*k*+*1*)) = *1*
⟨*proof*⟩ **lemma** *qf1-prime-exists*: *prime* (*4*∗*k*+*1*) ⟹ *is-sum2sq-nat* (*4*∗*k*+*1*)
⟨*proof*⟩ **lemma** *fermat-two-squares*: **assumes** *prime p* (¬ [*p* = *3*] (*mod 4*))
shows *is-sum2sq-nat p*
⟨*proof*⟩ **lemma** *sots2*: **assumes** ⋀ *k*. *prime* (*4*∗*k*+*3*) ⟶ *even* (*multiplicity* (*4*∗*k*+*3*)

n)
shows *is-sum2sq-nat n* ⟨*proof*⟩

theorem *sum-of-two-squares*:
is-sum2sq-nat n ⟷ (∀ *k*. *prime* (*4*∗*k*+*3*) ⟶ *even* (*multiplicity* (*4*∗*k*+*3*) *n*))
⟨*proof*⟩ **lemma** *k-mod-eq*: (∀ *p*::*nat*. *prime p* ∧ [*p* = *3*] (*mod 4*) ⟶ *P p*) = (∀ *k*. *prime* (*4*∗*k*+*3*) ⟶ *P* (*4*∗*k*+*3*))
⟨*proof*⟩

theorem *sum-of-two-squares′*:
is-sum2sq-nat n ⟷ (∀ *p*. *prime p* ∧ [*p* = *3*] (*mod 4*) ⟶ *even* (*multiplicity p n*))
⟨*proof*⟩

theorem *sum-of-two-squares-prime*: **assumes** *prime p*
shows *is-sum2sq-nat p* = [*p*≠*3*] (*mod 4*)
⟨*proof*⟩

end

end

1 Lagrange's four-square theorem

theory *FourSquares*
imports *HOL−Number-Theory.Number-Theory*
begin

context

fixes *sum4sq-nat* :: *nat* ⇒ *nat* ⇒ *nat* ⇒ *nat* ⇒ *nat*
defines *sum4sq-nat a b c d* ≡ *a*^*2*+*b*^*2*+*c*^*2*+*d*^*2*

fixes *is-sum4sq-nat* :: *nat* ⇒ *bool*
defines *is-sum4sq-nat n* ≡ (∃ *a b c d*. *n* = *sum4sq-nat a b c d*)

begin

private lemma *best-division-abs*: (*n*::*int*) > *0* ⟹ ∃ *k*. *2* ∗ |*a* − *k*∗*n*| ≤ *n*
⟨*proof*⟩

Shows that all nonnegative integers can be written as the sum of four squares. The proof consists of the following steps:

- For every prime $p = 2n + 1$ the two sets of residue classes

$$\{x^2 \bmod p \mid 0 \le x \le n\} \text{ and } \{-1 - y^2 \bmod p \mid 0 \le y \le n\}$$

  both contain $n + 1$ different elements and therefore they must have at least one element in common.

- Hence there exist x, y such that $x^2 + y^2 + 1^2 + 0^2$ is a multiple of p.

- The next step is to show, by an infinite descent, that p itself can be written as the sum of four squares.
- Finally, using the multiplicity of this form, the same holds for all positive numbers.

private definition
sum4sq-int :: *int* × *int* × *int* × *int* ⇒ *int* **where**
sum4sq-int = (λ(*a*,*b*,*c*,*d*). *a*^2+*b*^2+*c*^2+*d*^2)

private definition
is-sum4sq-int :: *int* ⇒ *bool* **where**
is-sum4sq-int n ⟷ (∃ *a b c d*. *n* = *sum4sq-int*(*a*,*b*,*c*,*d*))

private lemma *mult-sum4sq-int*: *sum4sq-int*(*a*,*b*,*c*,*d*) ∗ *sum4sq-int*(*p*,*q*,*r*,*s*) =
sum4sq-int(*a*∗*p*+*b*∗*q*+*c*∗*r*+*d*∗*s*, *a*∗*q*−*b*∗*p*−*c*∗*s*+*d*∗*r*,
a∗*r*+*b*∗*s*−*c*∗*p*−*d*∗*q*, *a*∗*s*−*b*∗*r*+*c*∗*q*−*d*∗*p*)
⟨*proof*⟩ **lemma** *sum4sq-int-nat-eq*: *sum4sq-nat a b c d* = *sum4sq-int* (*a*, *b*, *c*, *d*)
⟨*proof*⟩ **lemma** *is-sum4sq-int-nat-eq*: *is-sum4sq-nat n* = *is-sum4sq-int* (*int n*)
⟨*proof*⟩ **lemma** *is-mult-sum4sq-int*: *is-sum4sq-int x* ⟹ *is-sum4sq-int y* ⟹ *is-sum4sq-int* (*x*∗*y*)
⟨*proof*⟩ **lemma** *is-mult-sum4sq-nat*: *is-sum4sq-nat x* ⟹ *is-sum4sq-nat y* ⟹ *is-sum4sq-nat* (*x*∗*y*)
⟨*proof*⟩ **lemma** *mult-oddprime-is-sum4sq*: ⟦ *prime* (*nat p*); *odd p* ⟧ ⟹
∃ *t*. 0<*t* ∧ *t*<*p* ∧ *is-sum4sq-int* (*p*∗*t*)
⟨*proof*⟩ **lemma** *zprime-is-sum4sq*: *prime* (*nat p*) ⟹ *is-sum4sq-int p*
⟨*proof*⟩ **lemma** *prime-is-sum4sq*: *prime p* ⟹ *is-sum4sq-nat p*
⟨*proof*⟩

theorem *sum-of-four-squares*: *is-sum4sq-nat n*
⟨*proof*⟩

end

end

References

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