# Cauchy's Mean Theorem and the Cauchy-Schwarz Inequality 

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## Abstract

This document presents the mechanised proofs of two popular theorems attributed to Augustin Louis Cauchy - Cauchy's Mean Theorem and the Cauchy-Schwarz Inequality.

## Chapter 1

## Cauchy's Mean Theorem

theory CauchysMeanTheorem<br>imports Complex-Main<br>begin

### 1.1 Abstract

The following document presents a proof of Cauchy's Mean theorem formalised in the Isabelle/Isar theorem proving system.
Theorem: For any collection of positive real numbers the geometric mean is always less than or equal to the arithmetic mean. In mathematical terms:

$$
\sqrt[n]{x_{1} x_{2} \ldots x_{n}} \leq \frac{x_{1}+\ldots+x_{n}}{n}
$$

We will use the term mean to denote the arithmetic mean and gmean to denote the geometric mean.

## Informal Proof:

This proof is based on the proof presented in [1]. First we need an auxiliary lemma (the proof of which is presented formally below) that states:
Given two pairs of numbers of equal sum, the pair with the greater product is the pair with the least difference. Using this lemma we now present the proof -
Given any collection $C$ of positive numbers with mean $M$ and product $P$ and with some element not equal to $M$ we can choose two elements from the collection, $a$ and $b$ where $a>M$ and $b<M$. Remove these elements from the collection and replace them with two new elements, $a^{\prime}$ and $b^{\prime}$ such that $a^{\prime}=M$ and $a^{\prime}+b^{\prime}=a+b$. This new collection $C^{\prime}$ now has a greater product $P^{\prime}$ but equal mean with respect to $C$. We can continue in this fashion until we have a collection $C_{n}$ such that $P_{n}>P$ and $M_{n}=M$, but $C_{n}$ has all its elements equal to $M$ and thus $P_{n}=M^{n}$. Using the definition of geometric and arithmetic means above we can see that for any collection of positive
elements $E$ it is always true that gmean $\mathrm{E} \leq$ mean E . QED.
[1] Dorrie, H. "100 Great Problems of Elementary Mathematics." 1965, Dover.

### 1.2 Formal proof

### 1.2.1 Collection sum and product

The finite collections of numbers will be modelled as lists. We then define sum and product operations over these lists.

## Sum and product definitions

```
notation (input) sum-list (\sum:- [999] 998)
notation (input) prod-list (П:- [999] 998)
```


## Properties of sum and product

We now present some useful properties of sum and product over collections.
These lemmas just state that if all the elements in a collection $C$ are less (greater than) than some value $m$, then the sum will less than (greater than) $m *$ length $(C)$.

```
lemma sum-list-mono-lt [rule-format]:
    fixes xs::real list
    shows xs \not=[]^(\forallx\in set xs. }x<m
        \longrightarrow ( ( \sum : x s ) < ( m * ( r e a l ~ ( l e n g t h ~ x s ) ) ) )
<proof>
```

lemma sum-list-mono-gt [rule-format]:
fixes xs::real list
shows $x s \neq[] \wedge(\forall x \in$ set $x s . x>m)$
$\longrightarrow\left(\left(\sum: x s\right)>(m *(\right.$ real $($ length $\left.x s)))\right)$
proof omitted
〈proof〉
If $a$ is in $C$ then the sum of the collection $D$ where $D$ is $C$ with $a$ removed is the sum of $C$ minus $a$.

```
lemma sum-list-rmv1:
    \(a \in\) set \(x s \Longrightarrow \sum:(\) remove1 \(a x s)=\sum: x s-\left(a::{ }^{\prime} a::\right.\) ab-group-add \()\)
\(\langle p r o o f\rangle\)
```

A handy addition and division distribution law over collection sums.
lemma list-sum-distrib-aux:

```
    shows \(\left(\sum: x s /\left(n::{ }^{\prime} a\right.\right.\) :: archimedean-field \(\left.)+\sum: x s\right)=(1+(1 / n)) * \sum: x s\)
〈proof〉
lemma remove1-retains-prod:
    fixes \(a\) and \(x s:: ' a\) :: comm-ring-1 list
    shows \(a:\) set \(x s \longrightarrow \Pi: x s=\Pi:(\) remove \(1 a x s) * a\)
    (is ? \(P x s\) )
\(\langle p r o o f\rangle\)
```

The final lemma of this section states that if all elements are positive and non－zero then the product of these elements is also positive and non－zero．

```
lemma el-gt0-imp-prod-gt0 [rule-format]:
    fixes xs::'a :: archimedean-field list
    shows }\forally.y:\mathrm{ set xs }\longrightarrowy>0\Longrightarrow\Pi:xs>
\langleproof\rangle
```


## 1．2．2 Auxiliary lemma

This section presents a proof of the auxiliary lemma required for this theo－ rem．

```
lemma prod-exp:
    fixes \(x\) ::real
    shows \(4 *(x * y)=(x+y)\) 〔2 \(-(x-y)^{\wedge}\) 〔
    \(\langle p r o o f\rangle\)
lemma abs-less-imp-sq-less [rule-format]:
    fixes \(x::\) real and \(y::\) real and \(z::\) real and \(w::\) real
    assumes diff: abs \((x-y)<a b s(z-w)\)
    shows \((x-y) \wedge 2<(z-w)^{\wedge}\) ค
\(\langle p r o o f\rangle\)
```

The required lemma（phrased slightly differently than in the informal proof．） Here we show that for any two pairs of numbers with equal sums the pair with the least difference has the greater product．

```
lemma le-diff-imp-gt-prod [rule-format]:
    fixes }x::\mathrm{ real and }y::real and z::real and w::real
    assumes diff:abs (x-y)<abs (z-w) and sum: }x+y=z+
    shows }x*y>z*
<proof\rangle
```


## 1．2．3 Mean and GMean

Now we introduce definitions and properties of arithmetic and geometric means over collections of real numbers．

## Definitions

Arithmetic mean

## definition

$$
\begin{aligned}
& \text { mean }::(\text { real list }) \Rightarrow \text { real } \text { where } \\
& \text { mean } s=\left(\sum: s / \text { real }(\text { length } s)\right)
\end{aligned}
$$

Geometric mean

## definition

```
gmean :: (real list)=>real where
gmean s = root (length s) (\Pi:s)
```


## Properties

Here we present some trivial properties of mean and gmean.

```
lemma list-sum-mean:
    fixes \(x s\) :: real list
    shows \(\sum: x s=((\) mean \(x s) *(\) real \((\) length \(x s)))\)
\(\langle\) proof \(\rangle\)
lemma list-mean-eq-iff:
    fixes one::real list and two::real list
    assumes
        se: \(\left(\sum: o n e=\sum: t w o\right)\) and
        le: \((\) length one \(=\) length two \()\)
    shows (mean one \(=\) mean two)
\(\langle p r o o f\rangle\)
lemma list-gmean-gt-iff:
    fixes one::real list and two::real list
    assumes
        gz1: :one \(>0\) and \(g z 2: \Pi:\) two \(>0\) and
        ne1: one \(\neq[]\) and ne2: two \(\neq[]\) and
        pe: ( \(\Pi\) :one \(>\boldsymbol{\Pi}:\) two \()\) and
        le: (length one = length two)
    shows (gmean one \(>\) gmean two)
    〈proof〉
```

This slightly more complicated lemma shows that for every non-empty collection with mean $M$, adding another element $a$ where $a=M$ results in a new list with the same mean $M$.

```
lemma list-mean-cons [rule-format]:
    fixes xs::real list
    shows xs \not=[]\longrightarrow mean ((mean xs)#xs) = mean xs
<proof\rangle
```

For a non-empty collection with positive mean, if we add a positive number to the collection then the mean remains positive.

```
lemma mean-gt-0 [rule-format]:
    \(x s \neq[] \wedge 0<x \wedge 0<(\) mean \(x s) \longrightarrow 0<(\) mean \((x \# x s))\)
\(\langle p r o o f\rangle\)
```


### 1.2.4 list-neq, list-eq

This section presents a useful formalisation of the act of removing all the elements from a collection that are equal (not equal) to a particular value. We use this to extract all the non-mean elements from a collection as is required by the proof.

## Definitions

list-neq and list-eq just extract elements from a collection that are not equal (or equal) to some value.

## abbreviation

list-neq $::\left({ }^{\prime} a\right.$ list $) \Rightarrow{ }^{\prime} a \Rightarrow$ ('a list) where
list-neq xs el $==$ filter $(\lambda x . x \neq e l) x s$

## abbreviation

list-eq :: ('a list) $\Rightarrow{ }^{\prime} a \Rightarrow$ ('a list) where
list-eq $x s$ el $==$ filter $(\lambda x . x=e l) x s$

## Properties

This lemma just proves a required fact about list-neq, remove1 and length.

```
lemma list-neq-remove1 [rule-format]:
    shows \(a \neq m \wedge a\) : set xs
    \(\longrightarrow\) length (list-neq (remove1 a xs) \(m\) ) < length (list-neq xs \(m\) )
    (is ?A \(x s \longrightarrow\) ? \(B x s\) is ?P \(x s\) )
\(\langle p r o o f\rangle\)
```

We now prove some facts about list-eq, list-neq, length, sum and product.

```
lemma list-eq-sum [simp]:
    fixes xs::real list
    shows \sum:(list-eq xs m)=(m*(real (length (list-eq xs m)))}
<proof\rangle
lemma list-eq-prod [simp]:
    fixes xs::real list
    shows \Pi:(list-eq xs m)=(m^ (length (list-eq xs m)))
<proof\rangle
lemma sum-list-split:
    fixes xs::real list
    shows }\sum:xs=(\sum:(list-neq xs m) + \sum:(list-eq xs m))
\langleproof\rangle
lemma prod-list-split:
    fixes xs::real list
    shows \Pi:xs = (П:(list-neq xs m)* П:(list-eq xs m))
```

```
\langleproof\rangle
lemma sum-list-length-split:
    fixes xs::real list
    shows length xs = length (list-neq xs m) + length (list-eq xs m)
<proof\rangle
```


### 1.2.5 Element selection

We now show that given after extracting all the elements not equal to the mean there exists one that is greater then (or less than) the mean.

```
lemma pick-one-gt:
    fixes xs::real list and m::real
    defines m:m\equiv (mean xs) and neq: noteq \equiv list-neq xs m
    assumes asum: noteq = []
    shows \existse.e: set noteq }\wedgee>
<proof\rangle
lemma pick-one-lt:
    fixes xs::real list and m::real
    defines m: m \equiv (mean xs) and neq: noteq \equiv list-neq xs m
    assumes asum: noteq = []
    shows \existse. e : set noteq }\wedgee<
<proof>
```


### 1.2.6 Abstract properties

In order to maintain some comprehension of the following proofs we now introduce some properties of collections.

## Definitions

het: The heterogeneity of a collection is the number of elements not equal to its mean. A heterogeneity of zero implies the all the elements in the collection are the same (i.e. homogeneous).

## definition

```
het :: real list }=>\mathrm{ nat where
het l= length (list-neq l (mean l))
```

lemma het-gt-0-imp-noteq-ne: het $l>0 \Longrightarrow$ list-neq $l$ (mean $l) \neq[]$ $\langle p r o o f\rangle$
lemma het-gt-OI: assumes $a: a \in$ set xs and $b: b \in$ set xs and neq: $a \neq b$ shows het xs $>0$
$\langle p r o o f\rangle$
$\gamma-e q$ : Two lists are $\gamma$-equivalent if and only if they both have the same number of elements and the same arithmetic means.

## definition

```
\(\gamma-e q ~::((\) real list \() *(\) real list \()) \Rightarrow\) bool where
\(\gamma-e q a \longleftrightarrow\) mean \((f s t a)=\) mean \((\) snd \(a) \wedge\) length \((f s t a)=\) length \((\) snd \(a)\)
```

$\gamma-e q$ is transitive and symmetric.
lemma $\gamma$-eq-sym: $\gamma$-eq $(a, b)=\gamma-e q(b, a)$
$\langle p r o o f\rangle$

```
lemma \(\gamma\)-eq-trans:
\(\gamma-e q(x, y) \Longrightarrow \gamma-e q(y, z) \Longrightarrow \gamma-e q(x, z)\)
〈proof〉
```

pos: A list is positive if all its elements are greater than 0.

## definition

```
pos :: real list \(\Rightarrow\) bool where
pos \(l \longleftrightarrow(\) if \(l=[]\) then False else \(\forall e . e:\) set \(l \longrightarrow e>0)\)
```

lemma pos-empty $[$ simp $]$ : pos []$=$ False $\langle$ proof $\rangle$
lemma pos-single $[$ simp $]$ : pos $[x]=(x>0)\langle$ proof $\rangle$
lemma pos-imp-ne: pos $x s \Longrightarrow x s \neq[]\langle$ proof $\rangle$
lemma pos-cons [simp]:
$x s \neq[] \longrightarrow \operatorname{pos}(x \# x s)=$
(if $(x>0)$ then pos xs else False)
(is? P $x$ xs is ? A $x s \longrightarrow$ ? $S x x s$ )
$\langle p r o o f\rangle$

## Properties

Here we prove some non-trivial properties of the abstract properties.
Two lemmas regarding pos. The first states the removing an element from a positive collection (of more than 1 element) results in a positive collection. The second asserts that the mean of a positive collection is positive.

```
lemma pos-imp-rmv-pos:
    assumes (remove1 a xs) }\not=[]\mathrm{ pos xs shows pos(remove1 a xs)
<proof>
lemma pos-mean: pos xs \Longrightarrowmean xs > 0
<proof\rangle
```

We now show that homogeneity of a non-empty collection $x$ implies that its product is equal to $($ mean $x)$ ^ $($ length $x)$.
lemma prod-list-het0:
shows $x \neq[] \wedge$ het $x=0 \Longrightarrow \Pi: x=($ mean $x) \wedge($ length $x)$
$\langle p r o o f\rangle$
Furthermore we present an important result - that a homogeneous collection has equal geometric and arithmetic means.

```
lemma het-base:
    shows pos \(x \wedge\) het \(x=0 \Longrightarrow\) gmean \(x=\) mean \(x\)
\(\langle p r o o f\rangle\)
```


### 1.2.7 Existence of a new collection

We now present the largest and most important proof in this document. Given any positive and non-homogeneous collection of real numbers there exists a new collection that is $\gamma$-equivalent, positive, has a strictly lower heterogeneity and a greater geometric mean.

```
lemma new-list-gt-gmean:
    fixes \(x s\) :: real list and \(m\) :: real
    and \(n e q\) and \(e q\)
    defines
        \(m: m \equiv\) mean \(x s\) and
        neq: noteq \(\equiv\) list-neq xs \(m\) and
        \(e q: e q \equiv\) list-eq xs \(m\)
    assumes pos-xs: pos xs and het-gt-0: het xs \(>0\)
    shows
    \(\exists x s^{\prime}\). gmean \(x s^{\prime}>\) gmean \(x s \wedge \gamma-e q\left(x s^{\prime}, x s\right) \wedge\)
        het \(x s^{\prime}<\) het \(x s \wedge\) pos \(x s^{\prime}\)
\(\langle p r o o f\rangle\)
```

Furthermore we show that for all non-homogeneous positive collections there exists another collection that is $\gamma$-equivalent, positive, has a greater geometric mean and is homogeneous.

```
lemma existence-of-het0 [rule-format]:
    shows }\forallx.p=het x\wedgep>0\wedge pos x
    (\existsy.gmean y > gmean x}\wedge\gamma-eq(x,y)\wedge het y=0\wedge pos y
    (is ?Q p is }\forallx.(?A x p\longrightarrow?S S)
<proof\rangle
```


### 1.2.8 Cauchy's Mean Theorem

We now present the final proof of the theorem. For any positive collection we show that its geometric mean is less than or equal to its arithmetic mean.

```
theorem CauchysMeanTheorem:
    fixes z::real list
    assumes pos z
    shows gmean z\leqmean z
<proof\rangle
```

In the equality version we prove that the geometric mean is identical to the arithmetic mean iff the collection is homogeneous.

```
theorem CauchysMeanTheorem-Eq:
    fixes z::real list
    assumes pos z
```

```
    shows gmean z= mean z \longleftrightarrow het z=0
<proof>
corollary CauchysMeanTheorem-Less:
    fixes z::real list
    assumes pos z and het z>0
    shows gmean z< mean z
    <proof>
end
```


## Chapter 2

## The Cauchy-Schwarz Inequality

theory CauchySchwarz<br>imports Complex-Main<br>begin<br>$\langle$ proof $\rangle$

### 2.1 Abstract

The following document presents a formalised proof of the Cauchy-Schwarz Inequality for the specific case of $R^{n}$. The system used is Isabelle/Isar.
Theorem: Take $V$ to be some vector space possessing a norm and inner product, then for all $a, b \in V$ the following inequality holds: $|a \cdot b| \leq\|a\| *\|b\|$. Specifically, in the Real case, the norm is the Euclidean length and the inner product is the standard dot product.

### 2.2 Formal Proof

### 2.2.1 Vector, Dot and Norm definitions.

This section presents definitions for a real vector type, a dot product function and a norm function.

## Vector

We now define a vector type to be a tuple of (function, length). Where the function is of type nat $\Rightarrow$ real. We also define some accessor functions and appropriate notation.
type-synonym vector $=(n a t \Rightarrow$ real $) *$ nat

```
definition
    ith :: vector \(\Rightarrow\) nat \(\Rightarrow\) real (((-)_) \([80,100] 100)\) where
    ith \(v i=f s t v i\)
definition
    vlen \(::\) vector \(\Rightarrow\) nat where
    vlen \(v=\operatorname{snd} v\)
```

Now to access the second element of some vector $v$ the syntax is $v_{2}$.

## Dot and Norm

We now define the dot product and norm operations.

```
definition
    dot :: vector }=>\mathrm{ vector }=>\mathrm{ real (infixr - 60) where 
    dot a b = (\sumj\in{1..(vlen a)}. aj* * b )
```

definition

```
norm \(::\) vector \(\Rightarrow\) real \(\quad(\|-\| 100)\) where
norm \(v=\operatorname{sqrt}\left(\sum j \in\{1 . .(\right.\) vlen \(\left.v)\} . v_{j}{ }^{\wedge} 2\right)\)
```

Another definition of the norm is $\|v\|=\operatorname{sqrt}(v \cdot v)$. We show that our definition leads to this one.
lemma norm-dot:
$\|v\|=s q r t(v \cdot v)$
$\langle p r o o f\rangle$
A further important property is that the norm is never negative.
lemma norm-pos:
$\|v\| \geq 0$
$\langle p r o o f\rangle$
We now prove an intermediary lemma regarding double summation.

```
lemma double-sum-aux:
    fixes \(f:: n a t \Rightarrow\) real
    shows
    \(\left(\sum k \in\{1 . . n\} .\left(\sum j \in\{1 . . n\} . f k * g j\right)\right)=\)
    \(\left(\sum k \in\{1 . . n\} .\left(\sum j \in\{1 . . n\} .(f k * g j+f j * g k) / 2\right)\right)\)
\(\langle p r o o f\rangle\)
```

The final theorem can now be proven. It is a simple forward proof that uses properties of double summation and the preceding lemma.

```
theorem CauchySchwarzReal:
    fixes x::vector
    assumes vlen x = vlen }
    shows }|x\cdoty|\leq|x|*|y
<proof\rangle
end
```

