Arithmetic-Mean
Geometric-Mean
Inequalities
AM and GM

Def

1. The **arithmetic mean (AM)** of $x_1, \ldots, x_n$ is

$$\frac{x_1 + \cdots + x_n}{n}.$$
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   \[(x_1 \cdots x_n)^{1/n}.
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(x_1 \cdots x_n)^{1/n}.
\]

How do AM and GM compare when \(x_1, \ldots, x_n \in \mathbb{R}^+\)?
AM and GM: $n = 2$

Assume $x, y \in \mathbb{R}^+$. How do $\frac{x+y}{2}$ and $\sqrt{xy}$ compare?

Square both sides:

\[
x^2 + 2xy + y^2 \geq xy
\]

\[
x^2 - 2xy + y^2 \geq 0
\]

\[
(x - y)^2 \geq 0
\]

Proof also reveals that they are equal IFF $x = y$. Why $n = 2$? It will be the base case. And more!
AM and GM: $n = 2$

Assume $x, y \in \mathbb{R}^+$. How do $\frac{x+y}{2}$ and $\sqrt{xy}$ compare? Discuss.
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$$ \frac{x+y}{2} \geq \sqrt{xy} $$
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How do \( \frac{x+y}{2} \) and \( \sqrt{xy} \) compare? Discuss.

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\]

Square both sides

\[
\left( \frac{x + y}{2} \right)^2 \geq \sqrt{xy}^2
\]

\[
x^2 + 2xy + y^2 \geq 4xy
\]

\[
x^2 - 2xy + y^2 \geq 0
\]

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\[
\frac{x + y}{2} \geq \sqrt{xy}
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Square both sides

\[
\frac{x^2 + 2xy + y^2}{4} \geq xy
\]

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Why \( n = 2 \)?
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And more!
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Why $n = 2$? It will be the base case. And more!
The AM-GM Theorem

**Thm** For all $n \in \mathbb{N}$ and for all $x_1, \ldots, x_n \in \mathbb{R}^+$

\[
\frac{x_1 + \cdots + x_n}{n} \geq (x_1 \cdots x_n)^{1/n}
\]

Equality happens iff $x_1 = \cdots = x_n$. 
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Equality happens iff $x_1 = \cdots = x_n$. 
Recall To prove ($\forall n \geq 2)[P(n)]$ by induction you prove
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\(P(2)\)
\((\forall n \geq 2))[P(n) \rightarrow P(n + 1)].\)
Recall To prove \((\forall n \geq 2)[P(n)]\) by induction you prove \(P(2)\)
\((\forall n \geq 2))[P(n) \rightarrow P(n + 1)]\). From these two you can get to any \(n \geq 2\).
**Recall** To prove \((\forall n \geq 2)[P(n)]\) by induction you prove

- \(P(2)\)
- \((\forall n \geq 2))[P(n) \rightarrow P(n + 1)].\)

From these two you can get to any \(n \geq 2\).

Any set of rules that allows you to get to any number would work.
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$P(2)$

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\[
P(2) \text{ (we already did this).}
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\[P(2)\]
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We will prove
\[P(2)\text{ (we already did this).}\]
\[(\forall n)[(P(2) \land P(2^{n-1})) \rightarrow P(2^n)]]\]
Recall To prove \((\forall n \geq 2)[P(n)]\) by induction you prove
\[ P(2) \]
\[(\forall n \geq 2))[P(n) \rightarrow P(n + 1)].\]
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Recall: To prove \((\forall n \geq 2)[P(n)]\) by induction you prove
\[P(2)\]
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\[P(2)\] (we already did this).
\[(\forall n)[(P(2) \land P(2^{n-1})) \rightarrow P(2^n)]\]
\[(\forall n < m)[P(m) \rightarrow P(n)]\] (YES, \(n < m\)). (NOT a typo!)
From these implications we easily obtain \((\forall n)[P(n)].\)
\[ P(2^{n-1}) \implies P(2^n) \]

IH \[ \sum_{i=1}^{2^{n-1}} x_i \geq (\prod_{i=1}^{2^{n-1}} x_i)^{1/2^{n-1}} \]
\[ P(2^{n-1}) \implies P(2^n) \]

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**IS** \[
\sum_{i=1}^{2^n} x_i = \sum_{i=1}^{2^{n-1}} x_i + \sum_{i=2^{n-1}+1}^{2^n} x_i = \frac{1}{2} \left( \sum_{i=1}^{2^{n-1}} x_i + \sum_{i=2^{n-1}+1}^{2^n} x_i \right)
\]
\[ P(2^{n-1}) \implies P(2^n) \]

**IH** \[ \frac{\sum_{i=1}^{2^{n-1}} x_i}{2^{n-1}} \geq (\prod_{i=1}^{2^{n-1}} x_i)^{1/2^{n-1}} \]

**IS** \[
\frac{\sum_{i=1}^{2^n} x_i}{2^n} = \frac{\sum_{i=1}^{2^{n-1}} x_i}{2^n} + \frac{\sum_{i=2^{n-1}+1}^{2^n} x_i}{2^n} = \frac{1}{2} \left( \frac{\sum_{i=1}^{2^{n-1}} x_i}{2^{n-1}} + \frac{\sum_{i=2^{n-1}+1}^{2^n} x_i}{2^{n-1}} \right)
\]

\[
\geq \frac{1}{2} \left( (\prod_{i=1}^{2^{n-1}} x_i)^{1/2^{n-1}} + (\prod_{i=2^{n-1}+1}^{2^n} x_i)^{1/2^{n-1}} \right)
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\]

\[
\geq \frac{1}{2} \left( \left( \prod_{i=1}^{2^{n-1}} x_i \right)^{1/2^{n-1}} + \left( \prod_{i=2^{n-1}+1}^{2^n} x_i \right)^{1/2^{n-1}} \right)
\]

Next Slide
\[ P(2^{n-1}) \Longrightarrow P(2^n) \text{ (cont)} \]

\[ \geq \frac{1}{2} \left( \left( \prod_{i=1}^{2^{n-1}} x_i \right)^{1/2^{n-1}} + \left( \prod_{i=2^{n-1}+1}^{2^n} x_i \right)^{1/2^{n-1}} \right) \]
\( P(2^{n-1}) \implies P(2^n) \) (cont)

\[
\geq \frac{1}{2} \left( \left( \prod_{i=1}^{2^{n-1}} x_i \right)^{1/2^{n-1}} + \left( \prod_{i=2^{n-1}+1}^{2^n} x_i \right)^{1/2^{n-1}} \right)
\]

**Note** This is AM of 2 numbers! We use AM-GM-2 on it!
\[ P(2^{n-1}) \iff P(2^n) \text{ (cont)} \]

\[
\geq \frac{1}{2} (\left( \prod_{i=1}^{2^{n-1}} x_i \right)^{1/2^{n-1}} + \left( \prod_{i=2^{n-1}+1}^{2^n} x_i \right)^{1/2^{n-1}}) 
\]

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\[
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\]
\[ P(2^{n-1}) \implies P(2^n) \ (\text{cont}) \]

\[ \geq \frac{1}{2}((\prod_{i=1}^{2^{n-1}} x_i)^{1/2^{n-1}} + (\prod_{i=2^{n-1}+1}^{2^n} x_i)^{1/2^{n-1}}) \]

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\[ (\prod_{i=1}^{2^{n-1}} x_i)^{1/2^{n-1}} \times (\prod_{i=2^{n-1}+1}^{2^n} x_i)^{1/2^{n-1}} )^{1/2} \]
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\[
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\]

\[
\geq \left( \prod_{i=1}^{2^n} x_i \right)^{1/2^{n-1}} = \left( \prod_{i=1}^{2^n} x_i \right)^{1/2^n}.
\]
\[ n < m: \quad P(m) \implies P(n) \]

IH \((\forall x_1, \ldots, x_m) \left[ \frac{\sum_{i=1}^{m} x_i}{m} \geq \left( \prod_{i=1}^{m} x_i \right)^{1/m} \right] \).
\( n < m: \ P(m) \implies P(n) \)

**IH** \( (\forall x_1, \ldots, x_m)[\frac{\sum_{i=1}^{m}x_i}{m} \geq (\prod_{i=1}^{m}x_i)^{1/m}] \).

**IS** We care about \( \frac{x_1 + \cdots + x_n}{n} \).
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We need \( x_{n+1}, \ldots, x_m \) so we can use IH.
\( n < m: \ P(m) \implies P(n) \)

\textbf{IH} \ (\forall x_1, \ldots, x_m)[\frac{\sum_{i=1}^m x_i}{m} \geq (\prod_{i=1}^m x_i)^{1/m}].

\textbf{IS} \ We \ care \ about \ \frac{x_1 + \cdots + x_n}{n}.

We need \( x_{n+1}, \ldots, x_m \) so we can use \textbf{IH}.

\[
\begin{align*}
x_{n+1} = \cdots = x_m &= \frac{x_1 + \cdots + x_n}{n} = \alpha.
\end{align*}
\]
\( n < m: \quad P(m) \implies P(n) \)

**IH** \((\forall x_1, \ldots, x_m)[\frac{\sum_{i=1}^{m} x_i}{m} \geq (\prod_{i=1}^{m} x_i)^{1/m}]\).

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\[
x_{n+1} = \cdots = x_m = \frac{x_1 + \cdots + x_n}{n} = \alpha.
\]

And now we begin the proof, starting with \(\alpha\).
\[ n < m: \quad P(m) \implies P(n) \]

**IH** \((\forall x_1, \ldots, x_m)[\frac{\sum_{i=1}^{m} x_i}{m} \geq (\prod_{i=1}^{m} x_i)^{1/m}]\).

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x_{n+1} = \cdots = x_m = \frac{x_1 + \cdots + x_n}{n} = \alpha.
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And now we begin the proof, starting with \(\alpha\).

\[
\alpha = \frac{x_1 + \cdots + x_n}{n} = \frac{m}{n}(x_1 + \cdots + x_n).
\]
\[ n < m: \ P(m) \implies P(n) \ (\text{cont}) \]

\[ \alpha = \frac{x_1 + \cdots + x_n}{n} = \frac{m}{n} (x_1 + \cdots + x_n), \]
\[ n < m: \quad P(m) \implies P(n) \quad (\text{cont}) \]

\[ \alpha = \frac{x_1 + \cdots + x_n}{n} = \frac{m}{n} \left( \frac{x_1 + \cdots + x_n}{m} \right). \]

We want to write this as the mean of \( m \) elements.
\[ n < m: \ P(m) \implies P(n) \] (cont)

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$n < m$: $P(m) \iff P(n)$ (cont)

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We want to write this as the mean of $m$ elements.

\[ \frac{x_1 + \cdots + x_n}{n} = \frac{m}{n} \left( \frac{x_1 + \cdots + x_n}{m} \right) = \]

\[ \frac{x_1 + \cdots + x_n + \frac{m}{n} (x_1 + \cdots + x_n) - x_1 - \cdots - x_n}{m} = \]
\( n < m: \ P(m) \implies P(n) \) (cont)

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\alpha = \frac{x_1 + \cdots + x_n}{n} = \frac{m}{n} \left( \frac{x_1 + \cdots + x_n}{m} \right).
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We want to write this as the mean of \( m \) elements.

\[
\frac{x_1 + \cdots + x_n}{n} = \frac{m}{n} \left( \frac{x_1 + \cdots + x_n}{m} \right) = \frac{x_1 + \cdots + x_n + \frac{m}{n} (x_1 + \cdots + x_n) - x_1 - \cdots - x_n}{m} = \frac{x_1 + \cdots + x_n + \frac{m-n}{n} (x_1 + \cdots + x_n)}{m} = \frac{x_1 + \cdots + x_n + (m-n)\alpha}{m}
\]
\[ n < m: \ P(m) \implies P(n) \ (cont) \]

\[ \alpha = \frac{x_1 + \cdots + x_n + (m - n)\alpha}{m} \]
\( n < m: \ P(m) \implies P(n) \) (cont)

\[
\alpha = \frac{x_1 + \cdots + x_n + (m - n)\alpha}{m}
\]

We have the mean of \( m \) numbers! We can use IH!
\[ n < m: \quad P(m) \implies P(n) \quad (\text{cont}) \]

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\alpha = \frac{x_1 + \cdots + x_n + (m - n)\alpha}{m}
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\[
\alpha = \frac{x_1 + \cdots + x_n + (m - n)\alpha}{m} \geq ((\prod_{i=1}^{n} x_i \alpha^{m-n})^{1/m}
\]
$n < m$: $P(m) \implies P(n)$ (cont)

\[ \alpha = \frac{x_1 + \cdots + x_n + (m - n)\alpha}{m} \]

We have the mean of $m$ numbers! We can use IH!

\[ \alpha = \frac{x_1 + \cdots + x_n + (m - n)\alpha}{m} \geq ((\prod_{i=1}^{n} x_i)\alpha^{m-n})^{1/m} \]

\[ \alpha^m \geq ((\prod_{i=1}^{n} x_i)\alpha^{m-n}) \]
\[ \alpha = \frac{x_1 + \cdots + x_n + (m-n)\alpha}{m} \]

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\[ \alpha = \frac{x_1 + \cdots + x_n + (m-n)\alpha}{m} \geq ((\prod_{i=1}^{n} x_i)\alpha^{m-n})^{1/m} \]

\[ \alpha^m \geq ((\prod_{i=1}^{n} x_i)\alpha^{m-n}) \]

Multiply both sides by \( \alpha^{n-m} \) to get
\[ n < m: \ P(m) \implies P(n) \text{ (cont)} \]

\[ \alpha = \frac{x_1 + \cdots + x_n + (m - n)\alpha}{m} \]

We have the mean of \( m \) numbers! We can use IH!

\[ \alpha = \frac{x_1 + \cdots + x_n + (m - n)\alpha}{m} \geq ((\prod_{i=1}^{n} x_i)^{\alpha^{m-n}})^{1/m} \]

\[ \alpha^m \geq ((\prod_{i=1}^{n} x_i)^{\alpha^{m-n}}) \]

Multiply both sides by \( \alpha^{n-m} \) to get

\[ \alpha^n \geq \prod_{i=1}^{n} x_i \]
\[
\alpha = \frac{x_1 + \cdots + x_n + (m - n)\alpha}{m}
\]

We have the mean of \( m \) numbers! We can use IH!

\[
\alpha = \frac{x_1 + \cdots + x_n + (m - n)\alpha}{m} \geq \left( \prod_{i=1}^{n} x_i \alpha^{m-n} \right)^{1/m}
\]

\[
\alpha^m \geq \left( \prod_{i=1}^{n} x_i \alpha^{m-n} \right)
\]

Multiply both sides by \( \alpha^{n-m} \) to get

\[
\alpha^n \geq \left( \prod_{i=1}^{n} x_i \right)
\]

\[
\alpha \geq \left( \prod_{i=1}^{n} x_i \right)^{1/n}
\]
Why This Example?

This example is interesting since it uses a diff induction scheme.
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- Base Case
Why This Example?

This example is interesting since it uses a diff induction scheme. The key is that if you from:

- Base Case
- IS

you can reach any $n \in \mathbb{N}$, then $(\forall n)[P(n)]$. 